In-cave Environmental Monitoring Station Specification and Methods of Operation

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This paper describes the specification for an in-cave environmental monitoring station used to collect precise environmental data including air and soil temperatures, humidity, wind speed and direction, barometric pressure, water levels and other parameters. These stations are designed to be cave-proof and work for extended periods at 100% humidity levels, survive the rugged journey into a cave and retain their calibration over extended periods. The stations are designed to collect data for two years without changing batteries and to retain 25-years of collected data at normal rates.

Two station configurations are envisioned: an autonomous station and a tethered station. The autonomous station is designed for placement in a remote location that is visited periodically to extract the data and change batteries. The tethered station is essentially an autonomous station with an umbilical cord to provide power and data communications. The tethered station may also support gas sensors that cannot be supported on the autonomous station due to their relatively high power requirements.

The station supports a wide range of sensor configurations. The sensor configuration is determined at the time of manufacture and cannot be upgraded in the field. However, the sensor configuration may be upgraded by returning the station to the factory.

Data and Accuracy Requirements

The equipment needed for this study must operate at the extremes of available technology in order to provide useful information. For instance, the difference between 99.90% and 99.99% humidity can have a significant impact on the cave environment but is difficult to detect.

It is important to understand the difference between resolution, repeatability and accuracy. Resolution is the size of the smallest value that can be reported. For instance, if a sensor can represent 250 discrete levels and measures something with a range of 100 units, the resolution of the sensor is 0.4 units. Repeatability is the ability to report the same value when the sensor sees the identical conditions from either direction. For instance, a sensor with hysteresis may report one value when the condition is approached from one direction and a different value when approached from the opposite direction, which is undesirable. Accuracy is how close the value matches an absolute standard.

The calibration standard and repeatability determines accuracy. Technically, repeatable resolution beyond calibrated accuracy cannot be used because the additional resolved values cannot be validated. However, in most sensor systems it can be demonstrated that the resolved values are essentially linear between any two reasonably close points. If multiple sensors can be calibrated to return the same values between two chosen points and we can assume a linear progression between those two chosen points, any additional repeatable resolution can be used to resolve differences between the two sensors with a high degree of certainty.

Long term repeatability is also very important because monitoring stations are expected to be in place for extended periods of time - potentially for decades. It is certainly possible to create a portable transfer standard that can be used to check the calibration of field monitoring stations. However, if a discrepancy is found, the monitoring station must be return to the factory for recalibration.

In any given cave environmental air study, there may be 15 or more monitoring stations taking data simultaneously and a station may be moved to different locations during the life of the study. Each station location must be assigned a unique station identifier, such as the nearest survey station identifier so all data can be identified following the study. If a station is moved to a new location, it must be assigned a new station identifier. Each data sample must be uniquely self-identifying over any geographic area and time period.

The exact position and orientation of the station should be noted on a detailed cross sectional and plan map of the section of passage in which the station is placed. These cross sections are needed to accurately determine air mass flow and the influence of wall features on the station measurements.

The cave environment is very stable and changes take place over an extended period of time. A 10-minute sample period provides a good balance between power, data volume and the ability to detect relatively short events. However, when a station is first set up, especially near an entrance, a much shorter sample period may be used temporarily to be sure there are no rapid changes taking place that can influence the data collection. For instance, taking data every 10 seconds for the first hour may be appropriate. In any case, the station should allow easily configuration of sample periods.

All data samples must be synchronized and time stamped to allow simultaneous snapshot to be taken over a wide geographic area of the cave. Accuracy: 5 seconds per month.

Thermal and water transport potential are governed by temperature. Dry bulb temperature measures the temperature without regard to the moisture content. Wet bulb temperature measures the temperature relative to the evaporation potential of water. Dew point temperature measures the temperature at which water condenses from the air. Soil, water and other temperatures may also be useful. In order to measure relative humidity to 0.01%, it is necessary to measure temperature differentials to 0.001°C. Resolution: 0.0005°C, repeatability: 0.001°C, accuracy: 0.001°C.

Air pressure has a significant impact on air density, wind speed calculations and vapor pressure calculations. The difference in air pressures and densities is what cause winds to flow and determine their direction and speed. Tracking barometric pressure changes allows us to determine how external weather is affecting internal airflow. Resolution: 0.01 mbar, repeatability: 0.1 mbar, accuracy: 0.5 mbar.

The direct measurement of wind speed and direction is important for the calculation of air mass movement. Direct wind measurement is the only accurate way to detect and track steady-state wind flows. The positive wind direction is defined by a compass bearing and proper orientation of the wind sensor. Resolution: 0.5mm/s, repeatability: 1mm/s, accuracy: 1mm/s.

Some external sensors return pulses whenever an event occurs. These events are counted and reported for each sample period. Resolution: microprocessor instruction period, maximum count: 255 or 65535.

The level of CO_2, hydrogen sulfide and other gasses may be useful for certain environmental studies. These gas sensors usually consume considerable power and should be used sparingly. We have not determined the requirement for these measurements.

Calibration Standards

To achieve the desired levels of accuracy, laboratory calibration standards are required. The following standards are suggested:

- 5901C (Hart Scientific, www.hartscientific.com): $750, triple point of water calibration cell, 0.0100°C.
- 5903 (Hart Scientific, www.hartscientific.com): $3200, melting point of Gallium calibration cell, 29.7646°C.
- 740-16B (Paroscientific, www.paroscientific.com): $4200, precision digital barometer.

In addition to the calibration standards, special calibrating systems will be required to generate the specialized environments needed to ensure proper calibration.

Data Format

Station data will be logged in a standardized format. The primary goal is to provide the data in a form that is self-identifying, easy to read, easy to interpret and easy to validate.

Data will be encoded using the ASCII character set and formatted into lines. A line of text may be up to 200 characters long including the end of line sequence that terminates it. Lines in excess of this length can be broken into multiple lines by using a back slash ("\") to end the current line and to begin the next line. The parser discards the trailing back slash and the end of line sequence from the current line and the leading back slash from the following line. The end of line sequence consists of <CR><LF> (carriage return, line feed). Any line beginning with a forward slash ("/") is a comment and must be ignored when interpreting data. However, comment lines carry information that may be useful to a data analysis program and so should be retained with the data.

Data Types

The following data types are supported:

- Decimal Integer. <pad> is zero or more space characters needed to achieve the correct field length. <-nnnnnn> is a 6 digit negative number with a negative sign and <nnnnnnn> is a positive 7 digit number. In either case, leading zeros are suppressed. Length: 7.
    - <pad><-nnnnnn>
    - <pad><nnnnnnn>
- Hex. Hexadecimal number (0x00 to 0xFF). Length: 2.
- Boolean. 1 for true and 0 for false. Length: 1.
- Date/Time. The date and time encoded as yyyy.mm.dd hh:mm:ss, with fields corresponding to year, month, day, hour, minute and second, respectively. Time is always in 24-hour format in the specified time zone. Length: 19.
- Text. The field is <text><pad>, where <text> is a sequence of legal characters and <pad> is zero or more space characters needed to achieve the correct field length. Legal characters are: A-Z, a-z, _, 0-9. Legal characters are not case sensitive. Length: 16.

Station Identification Comment Block

The station shall periodically identify itself using a station identification comment block. The station identification comment block consists of a list of individual parameter comments that may have value when interpreting the data. Normally, the comment block will be generated immediately following station setup and once a day at 00:00:00 (midnight).

The following parameter comments are part of the Station Identification Comment Block.

- /Station ID: <SN>

  Station serial number. Each station is assigned a unique identifier at time of manufacture.

- /Version: <version>

  Station version number. The hardware and software use the same version sequence, so when either changes, the version number is incremented.

- /Station Location: <location> <description>

  Station location. <location> is the assigned station location identifier and <description> is a text description that continues to the end of line. We recommend the location be unique at the regional level so combining data from multiple projects will not produce location collisions. We recommend you include the cave name, region and country in the description.

- /Time: <date/time>

  Date and time. <date/time> is the current time.

- /Time zone: <utc-offset> <description>

  Time zone. <utc-offset> specifies the time zone offset from UTC and <description> is a text description that continues to the end of line. The time zone offset is specified as <+–><hh><mm> where <+–> is either plus or minus, <hh> is 2 digit hours and <mm> is two digit minutes, both with leading zeros if needed. Example, the time zone offset for Mountain Standard Time is -0700. The current time is always in the specified time zone.

- /Field: <n> <title> <description>

  Field number, name and description. <n> is the field number starting with 1, <title> is the field title used for field identification and <description> is a text description that continues to the end of line. Fields shall be arranged in sequence.

- /Field Calibration: <n> <sensor-type> <data>

  Type of sensor and the sensor calibration data for each field. The format of the data is sensor specific. <n> is the field number starting with 1, <sensor-type> and <data> are specified below. Fields shall be arranged in sequence.

  - CLK_v1 <center-temp> <temp-comp> <linear-comp>

    Calibration data for a real-time clock. <center-temp> is the center temperature for the temperature compensation, <temp-comp> is the temperature compensation in microseconds per °C squared, <linear-comp> is the linear compensation in minutes per second. In both compensations, a negative compensation value means the resulting absolute value is subtracted to achieve compensation.

  - RTD_v1 <low-temp> <low-count> <high-temp> <high-count>

    Calibration data for a 5K platinum RTD temperature sensor. <low-temp> is the low temperature in 0.001°C, <low-count> is the corresponding sensor count, <high-temp> is the high temperature in 0.001°C and <high-count> is the corresponding sensor count.

  - PSG_v1 <t> <p> [<temp.n> [<pressure.n> <pressure.n-count>]]

    Calibration data for a strain gage barometric pressure sensor. <t> is the number of temperature sets, <p> is the number of pressures per set, <temp.n> is the 2 digit temperature in °C, <pressure.n> is the pressure in 0.1mb and <pressure.n-count> is the corresponding sensor count.

  - WND_v1 <a> <b> <c>

    Calibration data for the wind sensors. This wind sensor is composed of 3 temperature sensors. <a>, <b> and <c> are the sensor type and calibration data for the positive, heated and negative sensors, respectively.

- /Positive Wind Direction: <heading>

  Wind direction for positive wind speeds. A wind with a negative speed is assumed to be 180° opposite.

Diagnostic Comment Blocks

The station shall periodically log any additional diagnostic, quality and status information using a diagnostic comment block. Since the items in the diagnostic comment block are event driven, only those comments that are relevant will be present. Normally, the comment block will be generated immediately following a station identification comment block and at any other time when information needs to be logged. However, redundant comments shall not be generated more than once per day.

The following comments are part of the Diagnostic Comment Block.

- /Field Quality: <n> <min> <max> <average> <standard deviation>

  The minimum value, maximum value, average value and the standard deviation for all readings. <n> is the field number. These values are reset after they are reported. Fields shall be arranged in sequence.

- /Battery Voltage: <voltage>

  Battery voltage for the current battery pack. Falling voltage is reported every 0.1V and generally represents the voltage under typical load. Voltage is considered sufficient if it remains above 3.5V.

- /Data Collected: <date/time>

  Date and time when data was collected from the station. Inserted following a successful data collection session when collecting data up to the present time. Not generated when collecting historic subsets (i.e., data that does not include the most recent data).

- /Parameter changed: <date/time>
  /Old: <parameter-comment>
  /New: <parameter-comment>

Parameter change. <date/time> is the date and time the parameter was changed. The next two lines specify the old and new values for the parameter, respectively. <parameter-comment> is a standard parameter comment. See the station identification comment block for more information on parameter comments.

- /Note: <text>

  Comment. <text> may be any text the station operator feels would be useful to someone interpreting the data at a later date.

Data Sample Field Identification Comment

The station shall generate a data field identification comment immediately prior to any data samples (i.e., following any other content). The field identifiers shall be field aligned and comma delimited for easy human readability. See the Field Identifier in the station identification comment block.

Data Sample

Each sample is a line of text, the format of which is described below. All fields are fixed length, padded with spaces and comma separated. The list of fields below is only an example of possible configurations - other configurations are also possible. Optional fields are only present when the represented sensor is present in the sensor configuration.

Each data line shall contain the following fields:

- Station location. The station location is a text identifier used to uniquely identify the physical location of a sample site. Type: text.
- Time stamp. The date and time the sample was taken. Type: date/time.
- Dry bulb. The dry bulb temperature in 0.001°C. Type: integer.
- Wet bulb. The wet bulb temperature in 0.001°C. Type: integer.
- Temperature 3 (optional). A third temperature in 0.001°C. Type: integer.
- Temperature 4 (optional). A fourth temperature in 0.001°C. Type: integer.
- Barometric pressure. The air pressure in 0.01mb. Type: integer.
- Wind speed and direction. Wind speed in 1mm/s with the sign indicating direction. Type: integer.
- Gas concentration 1 (optional). TBD. Type: integer.
- Gas concentration 2 (optional). TBD. Type: integer.
- Counter 1 (optional). An 8-bit event counter that is zeroed after each reading. Type: integer.
- Counter 2 (optional). A 16-bit event counter that is zeroed after each reading. Type: integer.
- Counter 3 (optional). A 16-bit event counter that is zeroed after each reading. Type: integer.
- Intruder. True if a light source was detected during the last sample period. Type: boolean.

- Checksum. Folded checksum to determine if the sample was received properly. Type: hexadecimal. The checksum is calculated using the following procedure:

  The 16-bit accumulator is initialized to 0. Repeat for each character in the string including the field separator prior to the checksum: multiply the accumulator by 2, add the character to the accumulator and check for overflow.

  Overflow occurs when any non-zero bits exist in the high order byte of the accumulator. When this happens, copy the high order byte as if it were a new character, clear the high order byte and add the copied value to the accumulator and again check for overflow.

The following is an example of a data record and field identification comment:

```
/       location,          date-time,drybulb,wetbulb,   baro,    wind,i,ck
CCNPLecha23     ,2001.01.31 14:38:22,  20357,  20352,  83671,       4,0,7E
```

Each standard sample record is 75 bytes long. Assuming a sample rate of 6 samples per hour and excluding comment blocks, the following data volumes result:

- 450 bytes (6 samples) per hour
- 10,800 bytes (144 samples) per day
- 75,600 bytes (1008 samples) per week
- 327,600 bytes (4368 samples) per month
- 3,931,200 bytes (52,416 samples) per year

Station Subsystems

The environmental monitoring station consists of many different subsystems. Each subsystem is covered below in detail.

Power

Autonomous and tethered stations share the same power system. Terminals will be provided for supplying external power, but in the event the external power is not capable of supplying sufficient power, the battery power system will automatically take over. This provides tethered stations with uninterrupted power.

Power is provided by two 6 volt battery packs. Each battery pack consists of 4 alkaline cells or 2 lithium cells wired in series. A cell capacity of 8000mAh is assumed and can be provided using premium quality D cells. One battery pack will be the primary battery pack and the other battery pack will be the secondary backup battery pack.

Each battery pack will have a status indicator consisting of a red and green LED. When a battery pack has sufficient power to take samples, the green LED will flash once every 10 seconds for 10ms driven at 10mA. When a battery pack is no longer capable of supplying enough power to take samples, the red LED will flash once every 10 seconds for 1ms driven at 10mA.

Each battery pack will be connected using a FET reverse polarity circuit to prevent circuit damage from reversed polarity. This circuit has the advantage that there is almost no forward voltage drop during normal operation.

Both battery packs will be tied to a common battery buss using logic to select exactly one of the two batter packs. A switch will determine which battery pack is the primary battery pack. The logic will detect a low primary battery pack voltage and automatically switch to the secondary battery pack.

The battery bus will feed a 3.3V linear LDO voltage regulator to power the main equipment bus. The main equipment buss will be capable of providing 25mA at 3.3V. Secondary precision 3.3V linear LDO voltage regulators will be used to generate local supplies where isolated power is required for instrumentation.

The primary battery pack provides sufficient power for 12 months assuming a power budget of 520mA seconds per sample at standard sample rates.

The following table shows the estimated power consumption for a standard configuration:

Item		**mA Seconds**
Microprocessor, storage, clock, power		100
Dry bulb temperature		1
Wet bulb temperature		350
Barometric pressure		25
Wind		25
	Total	503

Microprocessor Controller

The operation of the environmental monitoring station is controlled by a microprocessor. The microprocessor contains all programming, configuration and calibration data. The processor runs at 1MHz providing an instruction rate of 0.25MIPS.

The microprocessor provides three types of memory: SRAM, EEPROM and Flash. SRAM is used for scratch space and is initialized at power-up. EEPROM is used to retain field configuration data – data that changes with location and time. Flash is used to store programming, configuration and calibration data that is set at time of manufacture.

Configuration data includes station serial number, composite hardware/software version and sensor configuration.

The system shall be programmed in C and allow the use of an in-circuit emulator for development and testing. Software can be installed and upgraded as needed during development and manufacturing.

The microprocessor draws 2mA when active and 20µA when sleeping. During a normal sample period the microprocessor is active for 45 seconds and sleeping the rest for a total of 100mA seconds per sample period. This estimate covers the processor, real-time clock, data sample storage, power supply and other miscellaneous logic.

Data Sample Storage

Data samples are stored in a separate Flash memory system consisting of 128Mbytes of Flash organized as 528 bytes by 32 pages by 8192 blocks. No power is required to maintain the memory contents. This allows the station to store over 25 years of data at normal sample rates.

Data sample storage is initialized to 0 as part of the station initialization process. A jumper is required during the initialization process to prevent accidental destruction of data. Data sample storage should not be initialized in the field to prevent accidental data loss – the station itself is a backup for collected data.

A single pointer points to the first free (zero) byte of data memory. New data samples are written at this location and the pointer is updated. When memory fills up, data is no longer written. The pointer will be verified on startup by ensuring the previous two bytes form a valid end marker and the current byte is 0. If the pointer is invalid, the first 0 byte will be located and a valid end marker forced if necessary.

A single pointer points to the beginning of the data for the day on which data was collected. This ensures that any data set collected always starts with the station identification comment block. This pointer is updated whenever current data is collected from the station.

The station retains the last 5 data retrieval pointers along with the timestamp of when the data was collected. This data can be provided for reference.

The system also allows retrieval based on date ranges. All the data between the dates specified, inclusive, will be retrieved.

The data sample storage is included in the microprocessor power budget.

Real-time Clock

A real-time clock is used to keep track of the time and date. The time and date are used to synchronize the data samples across the network.

The station will use two time correction factors to maintain the required accuracy. The first correction factor is based on temperature sensor data – the crystal frequency changes according to a parabolic function of the temperature offset from its nominal operating temperature of 25°C. The second correction factor is based on manufacturing tolerances and parasitic circuit effects – crystals have an error even at their nominal operating temperature.

The time correction factor will be calculated in terms of adding or subtracting a second every N minutes. The temperature time correction factor will be recalculated at every sample interval.

The real-time clock is included in the microprocessor power budget.

General Sensor Interface

Pressure and temperature sensors will be designed to use a common sensor interface. This interface will support the following features:

- Sensor cable lengths of 30m (100 feet)
- Sensor control includes main power, auxiliary power, take reading, reading finished interrupt, transfer reading
- Sensor data will be read using a synchronized serial interface
- Sensor type, serial number and calibration data will be stored on the sensor. This feature will simplify calibration procedures and is therefore highly desirable. It also make field repair practical. Further investigation is needed to determine if this can be done reasonably.

Counting devices will be similarly configured except that data will be sent asynchronously. Counting can be configured to take place on the positive or negative going pulse edge.

Gate terminal blocks will be used to connect sensor cables to the main controller board. This provides a secure gas-tight connection that is highly resistant to corrosion.

Temperature Sensors

The temperature sensing system uses a 5kΩ platinum RTD (Resistance Temperature Detectors) in a half-bridge configuration fed directly into a 24-bit A/D. The circuit works by measuring the voltage across a temperature dependent resistance and comparing it to the voltage across a temperature stable resistance. The offset between these two readings is the sensor output.

The change in resistance in the RTD using the straight-line approximation between 0°C and 100°C is 3.85mΩ/°C/Ω or 19.25Ω/°C for a 5kΩ platinum RTD. A more accurate formula is: $R_t = R_0(1 + At + Bt^2 - 100Ct^3 + Ct^4)$, where R_t is the resistance at temperature t, R_0 is the nominal resistance at 0°C, A is 3.9083E-3, B is -5.775E-7 and C is -4.183E-12.

To generate a voltage across the RTD, it is necessary to drive a current though it. Power (I^2R) is dissipated in the RTD and a temperature offset error results. The still-air offset error due to self-heating is 0.2°C/mW (or 5mW/°C) when continuously powered. For a temperature offset error of 0.0005°C, we get an excitation power of 2.5µW, or an excitation current of 22µA. This produces a 424nV/0.001°C sense voltage, which is below the A/D noise floor of 750nV.

We believe we can safely raise the excitation current to 50µA without adversely affecting the accuracy of the readings. Moving to a higher excitation current raises the sense voltage just above the noise floor of the A/D and thus dramatically reduces the total number of readings required for an accurate sample. Using a reading duty cycle of 0.15 second per minute, 10 readings averaged per sample and the thermal mass of the sensor we expect to achieve the target accuracy and repeatability.

Using an excitation of 50µA, the power dissipation raises to 12.5µW for a still-air temperature offset of 0.0025°C if powered continuously – which we will not be doing. This produces a 962.5nV/0.001°C sense voltage, which is above the A/D noise floor of 750nV.

Note that increasing the standard reading frequency beyond the one per minute level will result in a decrease in sensor accuracy due to the increased self-heating offset.

The RTD sensor resistance is the first leg of the half bridge circuit and will vary from 5000Ω to 6925Ω between 0°C and 100°C, inclusive, respectively. Since the RTD changes resistance over a wide range, we will pick a value corresponding to 20°C (5385Ω) for the purposes of setting the current.

The reference resistor is the second leg of the half bridge circuit. The reference voltage should be twice the maximum voltage to be sensed which corresponds to a resistance of 14kΩ. The reference resistor must have a nearly 0ppm temperature coefficient and a 1% tolerance.

A third resistor sets the current. A value of 46.4kΩ will work nicely using a 3.3V precision voltage source and should have a low temperature coefficient and a 1% tolerance.

Each sensor is calibrated by noting the reading at each of two calibration points. A table of values is built fitting the R_t curve to these two calibration points so as to minimize the real-time computations required. Subsequent readings are then looked up in the table using interpolation to produce a temperature value.

The cold calibration takes place with the station in a cold box. The cold box and contents will be cooled to just above freezing. An ice mantle is formed in a triple point water cell. The sensors are inserted into the triple point water cell without touching the walls or each other. The calibration will continue until the readings have stabilized for 10 minutes.

The warm calibration takes place with the station in a warm box. The warm box and contents will be warmed to just below the melting point of gallium, with the sensors inserted into the calibration cell without touching the walls or each other. The temperature is then increased to just above the melting point of gallium. The calibration will continue until the readings have stabilized for 10 minutes.

The warm/cold box will be custom built with temperature regulation (solid state) and thick insulation. The temperature regulation should be to 0.1°C.

Each temperature sensor is powered by a separate precision 3.3V voltage reference and FET switch connected directly to the battery buss. Temperature readings should be taken with the station controller sleeping to eliminate noise from digital circuits. The series reference and sleeping controller ensure maximum power supply stability and minimum system noise while readings are taken.

Air temperature sensors should be mounted so as to minimize any heating affects from the station electronics. In general, air temperature sensors should be mounted on a line through the station perpendicular to the wind. Care should also be taken to minimize interactions with other sensors.

Each sensor reading takes roughly 400µA for 0.2 seconds, or less than 1mA second per sample (10 readings).

Barometric Sensor

The pressure sensing system uses a solid-state resistive bridge absolute pressure sensor fed into a 24-bit A/D via an instrumentation amplifier. The circuit works by measuring the voltage across the pressure strain gage bridge and comparing it to the voltage across a temperature stable resistance. The offset between these two readings is the sensor output.

The possible unit-to-unit variation between sensors is large due to the nature of how they are built and how they work. Sensitivity can vary by 30% while the thermal coefficient of 2150ppm/°C can vary by 12%.

The excitation current in the bridge produces a self-heating affect. The strain gage resistors are embedded in a thin semiconductor diaphragm and thus have a long thermal path and low thermal mass. As a result, the bridge must be allowed to thermally stabilize before taking readings. This can take 10 seconds to accomplish.

The nominal change in output voltage at 25°C is 1.50mV/V/PSI or 21.8µV/V/mb. Using a 3.3V voltage source, we get a 718nV/0.01mb sense voltage, which is slightly below the A/D noise floor of 750nV. Averaging 10 readings per sample will provide the required resolution.

The bridge has a resistance of 4.1kΩ and draws 800µA at 3.3V, dissipating 2.6mW. Each sample will require 20 seconds and consume 25mA seconds.

Humidity Sensor

Relative humidity is the relationship between how much water the air is holding and how much water the air is capable of holding. The air temperature and barometric pressure allow us to calculate the latter number. The former number requires us to make an indirect measure of water content. There are two common methods to measure water content: wet bulb temperature and dew point temperature. We are implementing the wet bulb temperature method.

A wet-bulb temperature sensor is a regular temperature sensor covered with a damp wicking cloth. The lower end of the wicking cloth is immersed in distilled water. An overturned 60cc container keeps the wick supplied with water. In situations where the relative humidity is not very close to saturation, a much larger container of water may be needed.

It is necessary to move air past the wet bulb in order to achieve maximum evaporation and thus maximum accuracy. Creating air movement is expensive electrically. A miniature fan will be used to move air up a pipe, with the sensor in a narrow window at the lower end of the pipe. The microprocessor uses a close-loop PWM technique to regulate power to the fan and keep the fan speed constant.

The fan draws 7mA at 3.3V with appropriate PWM regulation, dissipating 23mW. Starting the fan consumes 5 seconds of operational power. Each sample will require 45 seconds and consume 350mA seconds.

In situations where the relative humidity is below 95%, it may be expedient to use a conventional relative humidity sensor because extreme accuracy is no longer required. As you get further away from saturation, a difference of 1% is much less significant because a general drying condition is already well established. However, these conditions are normally only found in dryer locations or in locations with significant surface air exchange, such as near the entrance.

Wind Speed and Direction Sensor

The wind and direction sensing system uses three temperature sensors aligned on axis to the wind. The middle sensor contains a heating element. The system works by applying power to the heating element until the temperature stabilizes. The two flanking sensors are read to determine direction – one sensor should show a stable temperature while the other sensor should show an increase in temperature. Wind speed is determined by looking at both the maximum temperature obtained and the temperature decay rate.

An alternate wind sensor consists of two heated sensors. The system works by applying power to the heating elements until the temperatures stabilize. The temperature decay on both sensors is used to determine wind direction and flow. The probe that cools first is the windward probe and that probe will be used to determine decay time.

The temperature rise is 0.2°C/mW in still air. A 1°C rise requires 5mW or about 1.5mA at 3.3V applied to the heating element. The heating element will be a wound resistance wire of 2.2kΩ. The heating element will be powered for 15 seconds.

Wind speed and direction determination will take 25mA seconds.

Smoke from titanium tetrachloride can be used to verify proper operation of the wind sensor.

Event Counters

The counters count edge transitions. Counters provide both a positive edge and a negative edge trigger input. 8-bit counters can count up to 255 events per sample period while 16-bit counters can count up to 65535 events per sample period. The counters are read and zeroed at the end of every sample period. The event frequency cannot exceed the microprocessor instruction frequency.

The current microprocessor contains one 8-bit and one 16-bit counter that can be configured into the system without significant added cost. Future processors will offer three 16-bit counters.

The event counters are included with the microprocessor power budget.

Person Sensor

The presence of a person can create a perturbation in the sensor readings due to their extreme sensitivity. To help identify perturbations caused by people, we look for the presence of a light source and assume that any light source seen is caused by a human presence.

The detector is a photocell connected directly to the microprocessor's A/D converter. The A/D is sampled each time the microprocessor becomes active, which is normally once a second.

The person sensor is included with the microprocessor power budget.

Serial Communications Link

A two-way communications link with the station is necessary to configure the station and extract the data. Using an infrared (IR) link eliminates the normal problems associated with connectors. Most PDAs now contain a standard IR link that makes them a convenient method for configuring and extracting data. Data can be transferred at the rate of 90 seconds per megabyte.

Tethered stations will still use the PDA interface for configuration but will also send each data sample over the external serial port (RS-422 current loop). The bi-directional serial port will support a simple protocol to allow the central site to control the transfer of data.

The MetroWerks PalmOS development kit will be used to write software for the PDA that will enable station configuration, calibration and data retrieval.

The IR port is included with the microprocessor power budget. The external serial port will only be active when external power is available.

We are also looking at using a BlueTooth radio link for data retrieval instead of the IR link. The radio link is the latest PDA and mobile computing data link technology and provides several advantages over the IR port - mainly speed and distance. However, it is still new, expensive and not fully integrated into current PDAs. However, depending on the development cycle, this could be a viable alternative.

Component Selection

The following components are critical to the correct operation of the monitoring station. Other components are known to have multiple sources are not considered critical. Prices listed represent production volume pricing summer 2001 - excludes NRE and shipping.

PIC16LF877 (MicroChip, www.microchip.com): $10, 1MIPS embedded computer, 8K words of FLASH program memory, 368 bytes of RAM, 256 bytes EEPROM, 8 level stack, 33 I/O ports, 8-bit ALU, 10-bit A/D, 8-bit and 16 bit counter. This will be upgraded to an 18LF452 when they become available (summer 2002).

TH581000FT (Toshiba, www.toshiba.com): $320, 128Mbyte NAND flash RAM configured as 528 bytes by 32 pages by 8192 blocks.

DS32kHz (Maxim/Dallas Semiconductor, www.maxim-ic.com): $4, temperature compensated crystal oscillator.

DS1501 (Maxim/Dallas Semiconductor, www.maxim-ic.com): $4, real time clock, byte wide, settable alarm.

LTC2410 (Linear, www.linear.com): $19, low noise 24-bit A/D converter.

LT1460HCS3-3.3 (Linear, www.linear.com): $7, precision reference, 3.3V.

MAX8881EUT33-T (Maxim, www.maxim-ic.com): $1, 3.3V linear LDO voltage regulator with POK and reverse battery protection.

RTD - custom (Thermometrics Corporation, www.thermometrics.com, 818-886-3755, Tom): $55, 4wire, 5kΩ platinum wire wound, mounted inside a 3/16″ by 2″ 316 stainless steel tube, 2′ Teflon lead wires, 385 alpha.

Z201-14K000 (Vishay, www.vishay.com): $5, 14kΩ metal foil precision resistor, 0.2ppm/°C temperature coefficient.

C20-01 (Hankscraft Motors, www.hankscraft-motors.com): $10, motor with fan, 3V, 14mA.

24PCCFA6A (Honeywell, www.honeywell.com): $20, solid state resistive bridge absolute pressure sensor, hard mount, low drift, 0 – 15psia, 5KΩ.

Visor Pro (HandSpring, www.handspring.com): $450, PDA, PalmOS, flash card adapter, two 64Mb flash cards (two copies of one year's data for 15 stations).

PalmOS Developer's kit (MetroWerks, www.metrowerks.com): $550.

CCS Development System (CCS, www.ccsinfo.com): $700, C compiler, on-board debugger, and programmer.

Cost

The following cost estimates are approximate and have been rounded up so as to include associated costs not listed separately. Hardware cost estimates are listed separately from labor cost estimates. Hardware costs are based on volume purchases and will be higher if smaller quantities are purchased. The fully burdened cost of labor includes direct labor, associated taxes, administration overhead and facilities and is henceforth referred to as the labor cost. The labor rate used for these estimates is $46 per hour for manufacturing and $75 per hour for engineering. The hardware and labor costs combine to estimate the internal cost. The internal cost excludes marketing, sales and profit margins.

The estimated list price for one Environmental Monitoring Station is $4,500.

The following table shows the estimated production hardware cost for a standard station configuration (batch size: 20):

Item	**Cost**
Microprocessor, storage, clock, power	$350
Dry bulb temperature	$90
Wet bulb temperature	$115
Barometric pressure	$160
Wind	$280
Hardware	$55
Total	**$1040**

The following table shows the estimated manufacturing labor for a standard station configuration (quantity 20):

Item		**Hours**
Electronics assembly		4
Mechanical assembly		3
Configuration		2
Calibration		3
	Total Hours	**12**
	Total Cost	**$557**

The following table shows the estimated production station network hardware cost over and above the cost of the individual stations:

Item		**Cost**
PDA-based data collection		$800
	Total	**$800**

The following table shows the estimated cost for non-reoccurring hardware expenses associated with prototyping and production development:

Item		**Cost**
Station hardware for prototyping		$4,500
Development systems		$3,000
Production development		$6,000
Calibration standards		$8,500
Calibration chamber development		$4,000
Risk		$3,000
	Total	**$29,000**

The following table shows the estimated labor for prototyping and production development in 40-hour weeks:

Item		**Weeks**
Initial design and specification		4
Electronics prototyping		4
Mechanical prototyping		2
Software		6
Calibration system		6
Production development		4
System test		2
Risk		4
	Total Weeks	**32**
	Total Cost	**$96,000**

Disclaimer

This proposal is subject to change without notice. The implementation of this specification depends on the availability of funding and the validation of the design. We have worked hard to create a viable design and minimize the implementation risks.