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WATER QUALITY TELEMETRY

Final Progress Report

by

Duard S. Woffinden
and
Allen D. Kartchner

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INTRODUCTION

Water quality standards are now part of the legal code set up to control water pollution. In order to ascertain that these standards are being met, it is mandatory to monitor any river system over which control must be maintained. For optimum usefulness, data on the monitored variables should be available on a real time basis at any time throughout a 24-hour day. Remote sampling stations and a telemetry link represent the most practical means of accomplishing this end. There are presently systems available for telemetering water quality measurements. However, these systems are typically large physical installations, such as semi-permanent buildings or van-type trailers, which require external power and hard line telemetry coupling with a central data receiving station. A definite need exists for a small, low cost system capable of measuring the most commonly monitored parameters.

During Fiscal Year (FY) 1968, under an initial grant from the Federal Water Pollution Control Administration (FWPCA), the concept of using radio telemetry to transmit water quality data from a remote, battery-operated station was shown to be feasible. A field system was constructed which used battery operated, commercially available sensor units. The voltage outputs from each separate unit were adjusted by locally developed signal conditioning circuitry to obtain a voltage level compatible with a voltage controlled oscillator (VCO) which converted the signals to frequency form for transmission on a radio frequency (rf) carrier. Such an approach, although feasible, resulted in relatively high cost, duplication of circuitry, several different battery voltage levels for the different instrument requirements and a considerable waste of space in the remote station housing.

The second phase (FY 69) of the project had as its prime objectives the elimination of duplication in circuitry and battery sources and a reduction in size, weight, and cost. To achieve the objectives, new circuitry was developed for each individual sensor. Integrated circuits (IC) were used whenever possible. These IC's, besides reducing size and weight considerably, have excellent temperature stability characteristics and low operating currents. As each circuit was being developed, particular care was taken to see that common battery voltages could be used. Through this effort, three voltage levels were used (previously seven were required) and it was possible to get these from four 15 volt series-parallel connected batteries. The voltage levels used are $\pm 15$ volts and $+30$ volts. The $-15$ volts is supplied by two batteries in parallel because of the heavy drain during data transmission. The circuits were constructed on separate plug-in boards so that modules could be repaired or replaced easily.

The entire unit is housed in a portable fiber glass case (15”x15”x14”) with connectors for inputs from the sensors and for the cable to the antenna. The

FIELD STATION

Antenna Selection Relay

Transmitter → Power Switching Relay

Modulator

Voltage Controlled Oscillator

Channel Selection Switch

Signal Conditioning Circuits
  Temperature Sensor

Signal Conditioning Circuits
  Conductivity Sensor

Signal Conditioning Circuits
  Dissolved Oxygen Sensor

Signal Conditioning Circuits
  PH Sensor

Battery Power Supply

Voltage Monitor

Resonant Reed Relay

Timing And Control Circuits

Figure 5. Block diagram of telemetry field system.
Figure 6. Block diagram of telemetry base station.
Figure 7. Transmitter, receiver, control and power interconnections.
Control subsystem

The control subsystem, which is mounted on three plug-in boards, performs the following functions:

1. Switching the system from receive to transmit.
2. Timing individual samples.
3. Switching to each parameter in turn.
4. Converting sensor outputs from voltage to frequency to modulate the transmitter.
5. Returning the system to a standby condition.

Circuitry on these boards is shown in Figures 8, 9, and 10 and interconnections are shown in Figures 11 and 10.

The system is switched from receive to transmit when the receiver receives two audio tones each of which excites one of the resonant reeds. These tones are transmitted in series, the higher tone first followed by the lower. The schematic diagram of the resonant relay board (Figure 10) shows the two reeds and their associated circuits. The high frequency reed has a time constant circuit (20 megohms and .1 \( \mu \)fd) which holds Q302 in a conducting state while the low frequency reed turns on Q301. If the frequencies are transmitted in the reverse order, i.e. low-high, the system will not be actuated since Q301 has no holding circuit. Conduction by Q301 and Q302 causes a positive going voltage to appear at the gate of the SCR (Q303) and triggers it on. The voltage through the SCR goes out from pin A of P300 to pin A of P200 where it actuates the circuits on the timer and step switch control board.

Circuitry on the timer and step switch board is shown in Figure 9. The voltage turned on by the SCR goes through the normally closed contacts of K4 and does the following:

1. Applies voltage to the timing circuit in the base circuit of Q203 so that K4 is actuated after about 2 seconds thereby opening the circuit through the SCR and allowing it to reset.

2. Applies voltage to the base of Q205 to turn it on and thereby actuate K1 in the transmitter section. Power to actuate K1 comes from the -15 volt supply through terminal No. 1, K1 coil, terminal No. 2, J200 pin N, Q205 and the 47 ohm emitter resistor to ground. Once actuated K1 is latched on by the action of Q204 in the base circuit of Q205.

3. Applies voltage through pin R of J200 and pin R of J100 to the step relay K3 causing it to step one step and start the data transmission.

The closing of K1 in step 2 switches -15 V from the receiver to the transmitter and also switches the antenna from the receiver to the transmitter. The -15 V also comes out of pin 8 to pin P of J100 and J200. On the stepper and power relay board (Figure 8) this voltage actuates K2, the power control relay which applies power to the sensor circuits and the VCO.
Figure 8. Selector switch, power relay, and VCO circuit.
Figure 9. Timer and selector switch control circuit for determining sample duration and sequence.
Figure 10. Resonant reed relay circuit for selecting station address and initiating station reply.
Figure 11. Interconnections between the plug-in boards for the various parameter and control circuits.
Figure 12. Partial schematic showing calibrate-operate switch interconnections. The switch is shown in the operate position.
The closure of K1 not only switches the antenna and power from receiver to transmitter but also starts the sample interval timer (Figure 13). This is done by removing the -15 V potential from the gate of the injection transistor (Q202) thereby allowing the RC changing circuit to act and by applying -15 V to the base of Q201 so that it becomes conductive when the injection transistor fires. Firing of Q202 produces a positive pulse which is transmitted to the SCR and causes it to fire. Conduction by the SCR causes steps 1 and 3 to be repeated. Step 2 is not repeated since K1 is self-latching and in turn holds K2 actuated during the period of data transmission.

After each of the variables has been sampled by the sampling relay (K3) the next step produces the condition shown in Figure 14. When K3 contacts close on a "home" position a +15 volt signal is applied through the 47K resistor to the arm of the relay. This voltage causes a breakdown of the 1N4736.8 volt zener diode and produces a positive voltage on the base of Q204 thus cutting off conduction through it. With Q204 essentially an open circuit the base voltage of Q205 goes to zero cutting it off and thereby deenergizing K1. The entire system is then returned to a standby condition since K1 deenergizes K2 which removes all power from the sensors and VCO, and returns the antenna and power connections from transmitter to receiver. The positive voltage applied to the arm of K3 on the home position is fed also to the VCO input; however, it is limited by the zener diode to about 7 volts and its effect on the VCO output is not noticeable since its power is removed when K2 is deactivated. The zener diode acts as a switch. As long as the voltage on the arm is less than +6.8 volts it acts as an open circuit. When the voltage exceeds +6.8 V the zener fires and a positive voltage is fed to the base of Q204. The VCO input is 0 to +15 volts during normal operation so that the end of transmission circuitry is unaffected.

The variables monitored are, in order, supply voltage, temperature, conductivity, dissolved oxygen and pH. As each variable is sampled by the step switch, it is fed into the voltage controlled oscillator (VCO). The VCO accepts an input voltage from 0 to +5 volts and converts it to a frequency from 1572 to 1828. This conversion from volts to frequency is linear to within less than ±0.25% over a temperature range of -20 to +50°C. The output of the VCO is fed through pin N of J100 to terminal No. 4 of the transceiver. This input modulates the rf carrier for transmission to the ground station.

After each of the five variables has been sampled, the step switch steps to the home contact. As described earlier, when this contact closes, voltage fed from the +15 V battery is applied to the base of Q204 which causes Q205 to cut off and deenergize K1 and K2. With these relays deenergized all power is disconnected except for the standby power to the receiver and this condition is maintained until another set of interrogation signals is received.

The following descriptions cover the circuitry for monitoring each variable in the order sampled. Interconnections between the various plug-in boards are shown in Figure 11. Connections to the calibration check system are shown in Figure 12. The calibration check circuitry will insure proper operation of the entire system except for the parameter probes. This is accomplished by substituting a known input in place of the probes and observing an expected output. Should the expected output not be obtained, a system difficulty is indicated.
Figure 13. Timing circuit which controls sample duration.

Figure 14. Circuit which terminates data transmission and returns the system to standby condition.
Voltage monitor

Because alkaline rechargeable batteries used to power the system are irreparably damaged if allowed to discharge too much, a sensitive voltage monitor has been built in as one of the features of the system. Such a monitor will give adequate warning of the need for battery interchange by indicating both the discharge rate and condition. A schematic of this circuit is shown in Figure 15. The voltage actually monitored is the -15 volt supply battery since the drain on this battery is heavier than on any of the others. In practice the -15 volts is supplied by two 15 volt batteries in parallel. The output of the -16 volt supply is compared against a fixed reference obtained from the +15 volt supply through the use of a zener reference diode and a dropping resistor. By using one voltage to buck the other, a greater resolution on the voltage measurement can be obtained.

Temperature

A schematic diagram of the temperature circuitry is shown in Figure 16. The sensor used is a Yellow Springs Industries thermistor with a linear voltage-temperature relationship. This relationship is given mathematically by the equation

\[ E_o = 0.5348 \times 10^{-2} \times \frac{E_{in}}{\text{temp range } ^\circ C} \times T^\circ C + 0.135 \times E_{in} \]

The equation shows two component voltages, one temperature dependent and the other fixed. The fixed component is canceled by feeding an equal voltage of opposite polarity into the summing circuit of the operational amplifier. The temperature dependent voltage is fed on through the amplifier and used to modulate the VCO. Temperature readily can be measured to within about .3\(^\circ\)C and further resolution could be provided if it is ever needed.

Dissolved oxygen

The dissolved oxygen (DO) measurement is made by an Electronic Instruments Limited DO probe Model A15A. The EIL unit uses a concentric cylinder design. The inner lead anode is enclosed in a porous polyvinylchloride (PVC) shield that insulates the anode from the hollow surrounding silver cathode. The porous PVC insulator also allows the potassium bicarbonate electrolyte to form a conducting path between the electrodes. The entire assembly is covered by a polythene membrane which is permeable to oxygen but not to interfering ions. This probe has exhibited the longest unattended life and the most desirable characteristics of all the probes tested. It is self-generating and produces an output current of about 220\(^\mu\)A for air equilibrated water at 20\(^\circ\)C. This represents an oxygen concentration of 8.8 ppm or about the center of the desired range of 0 - 15 ppm. This electrode is temperature sensitive and changes at a rate of about 6\(^\%\)/\(^\circ\)C. This high rate could be a serious drawback without compensation except that: 1. Water temperature changes rather slowly. 2. The maximum to minimum temperature variations in the studied stream are less than 25\(^\circ\)C. 3. Knowing the existence of this 150\(^\%\) (6\(^\%\)/\(^\circ\)C x 25\(^\circ\)C) variation, it can be calibrated out of the reading by utilizing the temperature information obtained in the prior sample.
Figure 15. Supply voltage monitor circuit.
Figure 16. Water temperature measuring circuit.
The DO circuit, shown in Figure 17, utilizes an integrated circuit (IC) operational amplifier type μA741 as the active component between the DO probe and the VCO. This unit amplifies the output current from the probe. The output voltage of the amplifier is

\[ E_o = i_{in} \times R_{fb} \]

where

\[ i_{in} = 220 \mu A \text{ at } 20^\circ C \text{ and standard pressure (8.8 ppm)} \]
\[ R_{fb} = 8.2 \text{ K to } 10.2 \text{ K depending on its setting} \]
\[ E_o = 1.8 \text{ V to } 2.25 \text{ volts depending on } R_{fb} \text{ setting} \]

A dissolved oxygen concentration of 8.8 ppm represents about mid range of the expected values and should result in an output voltage of about 1/2 of the available 0 - 5 volt range.

**pH**

The measurement of pH (see Figure 18) is accomplished by the use of an Analytical Instruments permeable glass membrane combination probe and a Burr-Brown instrumentation amplifier. The probe produces an output voltage of approximately 60 MV per pH unit at 77°F. This output is influenced by temperature to the extent of reducing it to about 54 MV/pH at 0°C and increasing it to 74 MV/pH at 100 °C. Thus at constant pH the probe output will vary 20 MV/100°C or about .2 MV/°C. Since the temperature is accurately known, the probe output can readily be corrected to give an accurate pH reading.

The measurement of pH under field conditions involves extra difficulty not encountered in the laboratory because of the inherent electrical isolation provided by the sample holding beaker. In open streams an electrical ground is found instead of the desired isolation. The quality of this ground connection will vary markedly depending on the impurities in the water and the material of the stream bed. A diagram showing the conditions described is shown in Figure 19.

In Figure 19a it can be seen that in series with the two leakage resistances \( R_{L1} \) and \( R_{L2} \) is an extremely high resistance glass container. In contrast to this, in the field the leakage resistances are in series with the low resistance of the ground itself. In general \( R_{L1} \) is a rather low resistance and \( R_{L2} \) is high. In the laboratory case both of these resistors are negligible when compared to the resistance of the glass container. In the field case \( R_{L2} \) becomes the dominant leakage resistance and therefore must be carefully controlled and maintained at a high and constant resistance. In the telemetry system herein described, the leakage resistance is made high by employing an "instrumentation" type operational amplifier with an input impedance of \( 10^{11} \) ohms and a common mode impedance of \( 10^{11} \) ohms. With such high impedances it is necessary to use great care in construction both to eliminate stray leakage paths and to minimize noise pickup in the input. A triaxial cable is used to provide shielding and to eliminate leakage resistance variation in the ground circuit. Additional care must be exercised to see that the rf energy from the transmitter is not fed back into the probes. This is done by using rf shielding as necessary and by proper orientation of the directional antenna.
Figure 17. Dissolved oxygen measuring circuit.
Figure 18. pH measuring circuit.
Figure 19. Laboratory and field conditions with a combination pH probe.
Conductivity

The measurement of conductivity is accomplished by the use of a Honeywell probe. This probe is very rugged and immune to effects of fouling by deposits or growths on the electrodes. The electrodes are stainless steel and require no special coating so that the unattended service life is quite long (six months or more).

A schematic of the conductivity system is shown in Figure 20. For ease of installation the components were divided and placed on two plug-in boards as shown in the schematic diagram of Figures 21 and 2'.

In operation the 54 Hz signal is passed through amplifier A1 with a gain of about 3.2 and fed to the conductivity probe. The probe is constructed as shown in Fig. 23 with the center pin and the ring being excited by the signal from A1 through a liquid capacitor. This capacitor is used to prevent any DC current from flowing in the probe since even the slightest direct current would cause electrolysis and eventually erode away the probe elements. Built into the probe is a temperature compensating and high impedance circuit so that the probe elements are excited by an essentially constant current source. This voltage gradient produced across the probe elements by this current is sampled by the two sets of internal elements in parallel. The output from these two elements is fed through DC isolating capacitors into a differential amplifier A2 where it is amplified by a gain of about 1230. The output of A2 is a 500 Hz signal smaller in amplitude and 180° out of phase with the signal from the oscillator. These two signals are summed algebraically at the input of A2 so that the output of A1 represents the difference of the two inputs. The circuit of A1, conductivity probe, and A2 represents a negative feedback system wherein any changes in conductivity are immediately cancelled by corresponding changes in excitation signal. For instance, if the conductivity increases (resistivity and resistance decreases), the voltage measured between the sensing elements will decrease causing a decrease in the output of A2. This smaller signal will thus cancel the oscillator signal so that the output of A1 will increase. This increase will be transmitted to the probe where it will result in increasing the current and thus the voltage at the sensing elements. A larger voltage from the sensing elements will produce a larger A2 output and reduce the output of A1. This feedback loop will operate until a new stable state is reached corresponding to the new conductivity value. The 5 V output voltage is obtained by taking the signal from A1 through an isolation amplifier A3, a transformer, bridge rectifier, and filter. Circuit values have been chosen to provide an output of 5 volts DC when the conductivity is about 800 "microhos/cm. This represents a value safely above any measured in the Little Bear River. Lower values of conductivity will produce lower output voltages.

Base Station

The data gathering system used at the base station (see Figure 6) consists of a Motorola Console (25 watts transmitter power), an omnidirectional antenna (with approximately 9 db gain), an H-P signal generator, a Monsanto Counter and a locally constructed remote monitoring and control system. The two interrogating tones are generated in series by tuning the signal generator. These are monitored by the counter so that the exact frequency is transmitted in each case (audio
Figure 20. Conductivity measuring circuit.
Figure 21. Portion of conductivity circuit on plug-in board No. 1.
Figure 22. Portion of conductivity circuit on plug-in board No. 2.
oscillators are now available with push button frequency selection to facilitate this operation). The returning data signal is fed from the receiver to the monitor where it can be heard as well as counted. The frequency count for each parameter is written on a data sheet for later conversion to a particular value of the physical variable being measured by use of a calibration curve.

Figure 23. Construction of conductivity probe.
OPERATING EXPERIENCE

Laboratory calibration

The information received at the base station is in the form of a series of discrete audio frequencies. The parametric values are reconstituted by using calibration charts relating each audio frequency to a particular parameter value. These calibration charts are prepared in the laboratory before the system is installed in the river. Because the field system does not provide temperature compensation for pH and DO, it is necessary to prepare a family of calibration curves for each of these variables over the expected temperature range.

To accomplish the calibration, the probes are all placed in a constant temperature bath (Figure 24). The water in the bath is stirred so that the entire volume is at equilibrium and the flow requirements of the DO sensors are met. After establishing relationships at the ambient temperature, the temperature is varied over the desired range and the parameters are monitored by laboratory equipment and through the telemetry system. Subsequent swings through the temperature range with chemicals added to produce variations in DO, pH, and conductivity are made to complete the calibration. Prior to and after the completion of the probe calibration, the calibration check switch is switched through the five steps provided and the values represented by each step position for each variable are recorded. The fifth position (CW) reduces all inputs to zero and provides for an amplifier balance check in each circuit. The three intermediate positions substitute constant voltage levels which represent values of each variable over their ranges of interest. The first position (CCW) is the operate position.

Calibration charts for the voltage monitor and each parameter are shown in Figures 25 through 29.

Two minor problems were encountered in the process of calibration. Each concerned extraneous signal pickup by the probes. The first problem was a pickup of 60 Hz voltage from the heating element and stirrer motor of the constant temperature bath. This problem was alleviated by turning off both heater and motor immediately before each measurement was made. In this manner, flow continued past the DO probe long enough to obtain an accurate measurement. The second problem was a pickup of radio frequency energy from the telemetry transmitter. In the laboratory, this was avoided by disabling the rf transmitter and counting the VCO output directly. In the field where the transmitter is an integral part of the system this difficulty was resolved by using rf shielding and by physically separating the antenna from the rest of the system.
Figure 24. Laboratory setup for calibrating the system.
Figure 25. Voltage monitor calibration curve.
Figure 26. Temperature calibration curve.
Figure 27. Conductivity calibration curve.
Figure 29. pH calibration curve.
Field operation

The system was installed in the Logan River and interrogated from the base station. Periodic checks on system operation were made by means of independent chemical and electronic analysis.

The system worked satisfactorily although some difficulty was experienced with the pH, DO, and conductivity probes. The DO subsystem worked well until some floating debris caused a hole in the membrane. Several pH probes were used and operated well when initially installed; however, they exhibited very short effective lives in the river environment. Future operation would require a more robust probe. The conductivity probe continued to experience rf pickup when installed in the river. This was eliminated by installing a bypass capacitor across the signal leads from the probe. No trouble was experienced with the voltage monitoring of the batteries or the temperature system.
SYSTEM COSTS

It is difficult to separate development costs from production costs on a one system basis. However, a good estimate can be made of the parts cost on a low volume basis with the certain knowledge that the price will be less for a greater number (10 or more) of systems. On a mass production basis the labor costs can be substantially reduced although the exact reduction will depend on a number of somewhat intangible variables. The cost for one field site system monitoring four quality parameters is about $2200 for parts and probes and about $900 in fabrication labor for a total of $3100 per station as shown in Table 1. Of this total about $970 is for probes and signal conditioning circuits and the remainder is for the telemetering and control system.

A manual base station, as used for the present project, costs about $2000. A listing of the necessary equipment and their costs is shown in Table 2.

This represents the bare minimum necessary to interrogate one station or a network of stations with the data recorded manually. Even so, this basic system represents a substantial economy over the totally manual system in which an individual drives to the sampling site, dips in sample bottles, and returns the samples to the laboratory for analysis. Furthermore, the data can be collected on a well controlled time schedule without regard for inclement weather or other difficulties or inconveniences.
### Table 2
**Base Station Costs**

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<th>Item</th>
<th>Quantity</th>
<th>Description</th>
<th>Cost</th>
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<tr>
<td>Transmitter and receiver</td>
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<td>$500</td>
<td></td>
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<tr>
<td>Antenna omnidirectional</td>
<td>1 ea.</td>
<td>$162</td>
<td></td>
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<tr>
<td>Audio oscillator for generating</td>
<td>1 ea.</td>
<td>$490</td>
<td></td>
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<tr>
<td>Audio oscillator for generating</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interrogating signals—push button</td>
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<td></td>
<td></td>
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<tr>
<td>Frequency selection</td>
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<td></td>
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<tr>
<td>Counter to counter and display</td>
<td>1 ea.</td>
<td>$575</td>
<td></td>
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<tr>
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<td>Estimated labor for system</td>
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