NOAA Technical Memorandum ERL CMDL-13

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ABSTRACT. The design of an automatic tower measuring system mounted on a television transmitter tower in the southeastern United States is described in detail. We use NDIR Li-Cor 6251 analyzers for unattended, continuous measurements of carbon dioxide (CO_2) mixing ratio at three altitudes up to 496 m above the surface. Real-time control and data collection uses a 486 PC running under the multi-tasking operating system QNX. The CO_2 data show strong diurnal and seasonal variations and large vertical gradients. Comparison of our continental tower data with data from "background" sites should provide a strong constraint for regional and global models of terrestrial CO_2 fluxes.

1. INTRODUCTION

Carbon dioxide (CO_2) levels in the atmosphere have been monitored at many sites worldwide for up to 35 years [*Conway et al.*, 1988]. However, current sampling networks for CO_2 and other trace gases are heavily weighted toward the marine boundary layer, and terrestrial systems are greatly under-represented [*Tans*, 1991]. A project proposed by *Tans* [1991] is the establishment of an observational network in the continental United States to measure how much carbon dioxide, the major anthropogenic greenhouse gas, is being absorbed or lost by ecosystems. This strategy aims to determine CO_2 mixing ratios representative of continental areas, and thereby allow terrestrial net fluxes to be better quantified using global models of atmospheric transport. To minimize the effects of local sources and sinks on mixing ratio measurements, the methods were designed to measure CO_2 and other trace gases continuously on existing very tall towers. System design for the tower project began in May of 1991 and focused on building an unattended, automatic measuring system that would be accessible in real-time. Hardware and software were developed in subsequent months. In June 1992, we began continuous measurements of CO_2 on a 610-m tall television and FM radio transmitter tower (WITN Station) in a rural area of eastern North Carolina (35°21'55"N, 77°23'38"W, 9 m above sea level). Real-time control and data collection uses a PC 486 running under the multi-task operating system QNX (QNX Software Systems, Kanata, Ontario, Canada). Pre-processed data are compressed and then transmitted to Boulder each day by a 9600 baud modem. The software and hardware have been running smoothly from the beginning. In October of 1994, the second tall tower system was implemented and started continuous CO_2 measurements in Park Falls (WLEF Station), Wisconsin (45°56'43"N, 90°16'28"W).

2. ANALYSIS INSTRUMENT DESCRIPTION

Figure 1 shows a system block diagram for CO_2 measurements on the WITN tower. Tubes for trace gas sampling (1-cm inner diameter, DuPont Dekabon type 1300) were mounted on the tower with inlets at 51, 123, and 496 m above the ground, and sensors for wind speed and direction, temperature and humidity were placed at the same three levels. Air is continuously drawn through each of the tubes at a flow rate about 4-L min^{-1} using diaphragm pumps, and the residence time for air in the tube from the 496-m level is approximately 10 min. Studies in our laboratory and experience at other sites have shown that Dekabon tubing is inert with repeat to CO_2 at ambient levels. The sample air from each level is pressurized to about 70 kpa above ambient pressure and is then passed through a glass trap for liquid water maintained at about 4°C. The traps are continuously purged of water to minimize loss of CO_2 to the liquid phase. From each dried sample stream a flow of 100 cm^3 min^{-1} is diverted through a 16-position sampling valve (Valco Instruments, Houston, Texas), which is used to select between sample and calibration gas. The common port of each valve is connected to a mass flow controller (Tylan General, Torrence, California) that maintains a constant flow through a CO_2 analyzer. Before analysis, this air is further dried to a dew point of -25°C using a Nafion drier (Permapure, Toms River, New Jersey, model MD-250-72P Mini Drier), so that the water vapor interference and dilution effects are <0.1 ppm (parts per million by mole fraction) equivalent CO_2. Analysis for CO_2 mole fraction is carried out by IR absorption spectroscopy using Li-Cor (Linçoln, Nebraska) model 6251 analyzers. The reference cell of each analyzer is flushed at a flow rate of 10 cm^3 min^{-1} with a compressed gas standard containing ~330 ppm CO_2 in air.

The nonlinear response of the Li-Cor analyzers can be well approximated over the range of interest using a second-order polynomial. We calibrate the instruments with four standards spanning the range 330-420 ppm. Each standard is analyzed for 2 min during each calibration sequence, and calibrations are carried out every 3 hours. The root mean squares of the residuals from the four-point fits were generally less than 0.1 ppm, which provides an estimate of the precision of our measurements. Absolute accuracy for CO_2 is tied to the accuracy of our standards calibrated in our laboratory against World Meteorological Organization (WMO) standards. Each working standard tank lasts for several months. Once per month we compare the working standards to a set of four long-lived (years) "station" standards to assure long-term stability of the calibration. Overall accuracy and precision of the CO_2 mixing ratios is determined to be better than 0.2 ppm. The reference and sample cells are not pressure controlled and the instrument span is dependent on ambient pressure, as expected. Each Li-Cor is zeroed every 36 min using the 330 ppm standard to account for short-term drift in the instrument zero that varies somewhat with temperature. Linear interpolation in time of the data between each "zero" and calibration is used.

The supporting measurements include ambient pressure at the surface using an analog barometer (A.I.R., Inc., Boulder, Colorado), incident photosynthetically active radiation (PAR) using a Li-Cor model 190S quantum sensor, and soil temperature measured at 10 cm depth at 15 locations in a field adjacent to the tower and in the margin of a forest nearby. In addition, concentrations of radon-222 are being measured at 0.5, 51, 123 and 496 m levels above the ground that provide an excellent trace for soil and atmosphere gas exchange and continental air masses. Paired flasks (2.5 L) are collected weekly from the 496-m level for analysis for CH_4,

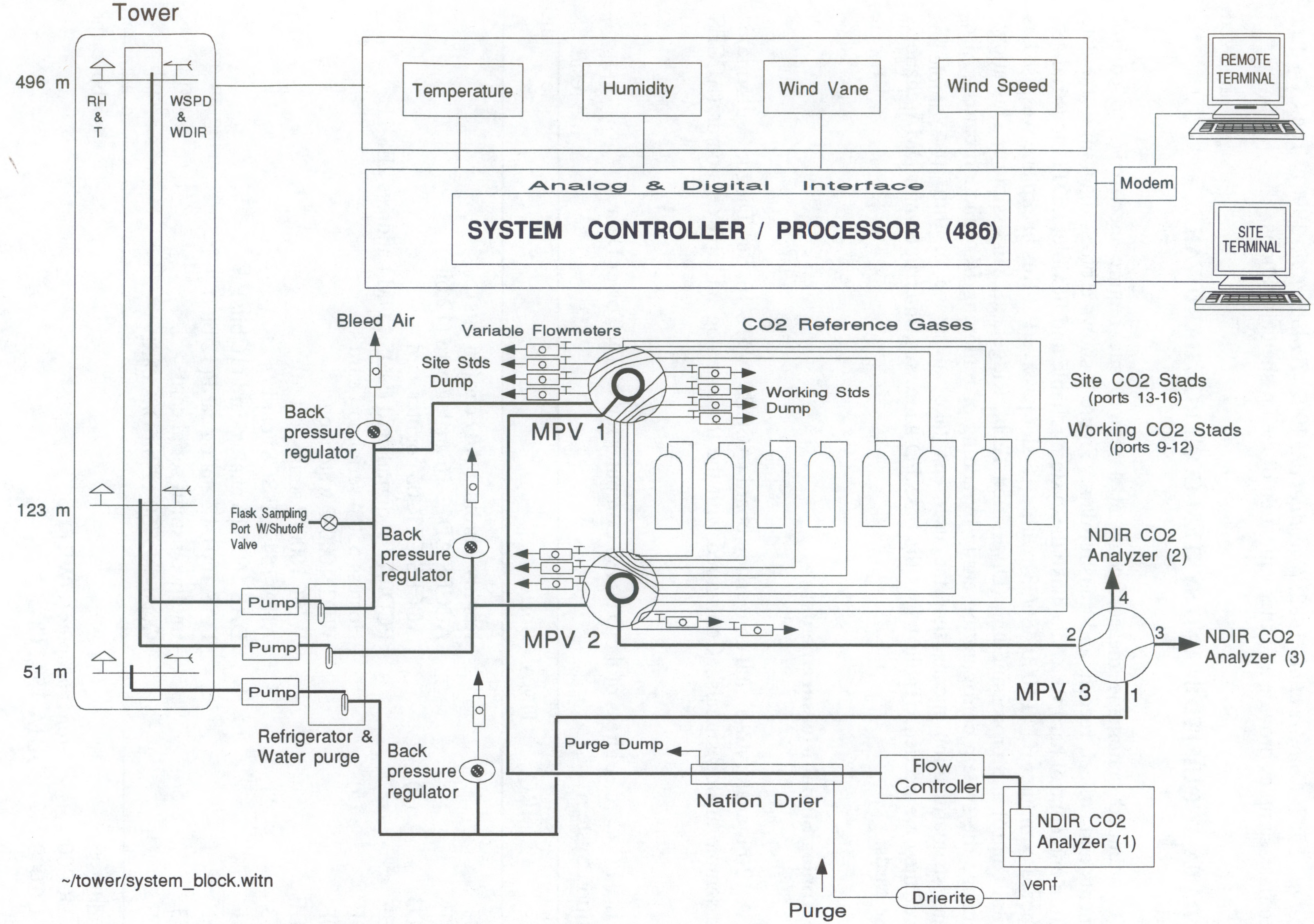


Figure 1. Instruments and data system for CO2 measurements on a 610 m TV transmitter tower in North Carolina

CO_2, CO, and the stable isotopes of C and O in CO_2, following standard CMDL procedures [*Steele et al.*, 1987; *Conway et al.*, 1988; *Novelli et al.*, 1992, *Trolier et al.*, 1996). The CO_2 data from the flask samples provide a further validation of the on-site calibrations.

3. DATA ACQUISITION AND SYSTEM CONTROL HARDWARE

Unattended, automatic measurements at a remote site require electronics to control experiments and collect, record, and transmit data. Figure 2 shows a block diagram of the data acquisition and control hardware. To make the system reliable and flexible, a DTI industrial 486 single-board computer (CAT1000 486/33) with a 15-slot passive PC-Bus backplane was used as the digital control and processing unit (Diversified Tech., Ridgeland, Mississippi). This allows us to change the system configuration easily by adding or removing I/O function cards. Also, hardware standardization means that the user can take advantage of third party products whenever they are needed. Table 1 lists the base I/O addresses, interrupts, and DMA channels for these cards.

3.1 Analog Signal Measurements

A 12-bit analog-to-digital conversion board (ACCES AD12-16, San Diego, California) is used to sample analog signals. Configured with the three analog multiplexer boards (ACCES

Table 1. I/O Card Address of the DTI 486 Computer for WITN Tower Data Acquisition System

Address	IRQ	DMA	Board
300-304	3		Keithly Chrom-1 A/D car (16 bits)
310-31F			ACCES AD12-16 analog card (12 bits)
2D0-2D3	(3)		ACCES CTR-05 counter card
2E0-2EF			PCDI072-P digital card (DOS COM4 address 2E8-2EF)
280-29F	(5)		Hostess 550 4 serial port card
308-30F			WDT 1000-P watchdog
2B8-2BF			WDT 1000-P serial port
330-333	11	5	AHA-1542CF SCSI card
340-34F		1	DAS 1602/16 analog card (16 bits)
360-36F			DAS 1601/12 analog card (12 bits)
350-353	5		Intellicon smart serial card
100-10F			Octagon 5750 12-bit D/A card

BIOS address:

DC000	Arcnet adapter (QWET)
CC000	AHA-1542 CF

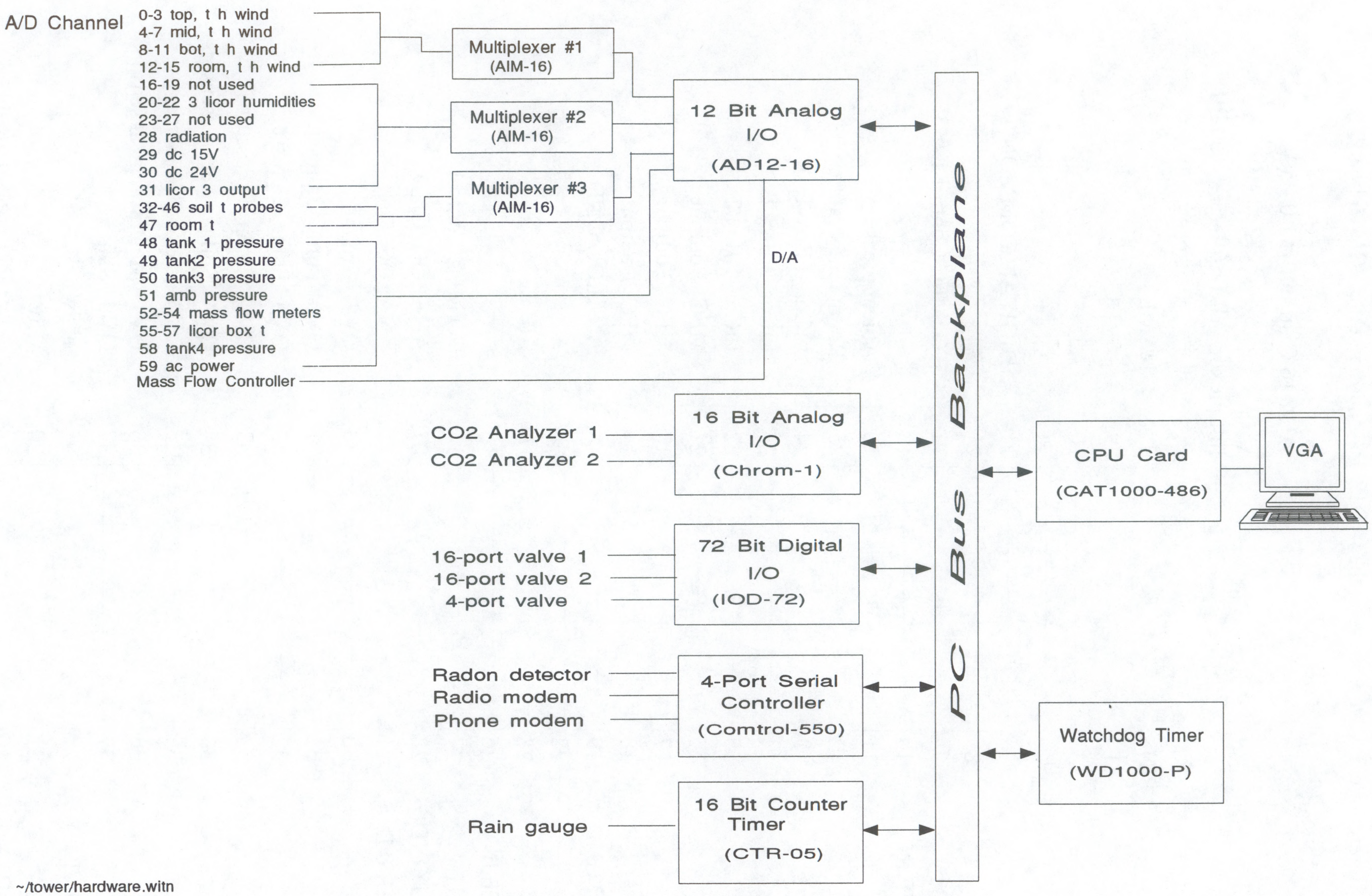


Figure 2. A block diagram of the data acquisition and control hardware on WITN tower

Figure 3. Interconnect wiring between the AD12-16 board and the AIM16 board

AIM-16 Gain set: #1 0 - 5 V
#2 0 -10 V

AD12-16		Multiplexor AIM-16	50 PIN
NAME	PIN	PIN	NAME
+5VDC	1	29	+5VDC
OP 3	3	10	A3
OP 1	4	8	A1
COM	7	11	DIGITAL COMMON
-5V REF	8	2	
D/A 0 OUT	9	12	TO MFC Control 1 & 3
D/A 0 REF IN	10	13	
CHL 15	11	26	Abient pressure
CHL 14	12	25	Room temperature
CHL 13	13	24	LiCor_3 Box T
CHL 12	14	23	LiCor_2 Box T
CHL 11	15	22	LiCor_1 Box T
CHL 10	16	21	MFC_3 output
CHL 9	17	17	MFC_2 output
CHL 8	18	16	MFC_1 output
ANALOG GND	19	18	ANALOG GND
OP 2	22	9	A2
OP 0	23	7	A0
D/A 1 REF IN	26	15	
D/A 1 OUT	27	14	TO MFC Control 2
ANALOG GND	28	27	ANALOG GND
COUNTER 0 IN	21	4	ANALOG GND
CHL 7	30	30	OV7 Ground
CHL 6	31	31	OV6 Pump_3 pressure
CHL 5	32	32	OV5 Pump_2 pressure
CHL 4	33	33	OV4 Pump_1 pressure
CHL 3	34	34	OV3 Soil temperture sensors
CHL 2	35	35	OV2 LiCor_3 Analyzer
CHL 1	36	36	OV1 Meteorological sensors
CHL 0	37	37	OV0 Skip
CTR 0 OUT	2	1	+15v
CTR 0 IN	21	20	-15v
CTR 2 OUT	20	3, 5, 6	G0, G1, G2 Programed Gain

~/tower/witn_aio16_at16.wrt

AIM16), the system provides 61 analog input channels. Figure 3 shows the wiring connections between the AD12-16 board and the AIM16 board. The analog inputs include wind speed, wind direction, air temperature, relative humidity, ambient pressure, pump pressure, soil temperature, room temperature and radiation. Except for an ambient pressure transducer signal (located inside the building), all of these analog signals are in current loops allowing signals to be transmitted over long distances while providing noise immunity. A custom designed DC amplifier is used to convert the output of the Li-Cor radiation sensor 0-20 μA to 0-5 volts (Figure 4). Having passed through the lightning protection boards, the analog signals from outside sensors are coupled into the three multiplexer boards via screw terminal blocks. Figure 5 shows wire connection for the lightning protection boards mounted in the rear panel plate. The three pump pressures (pressure in the tubes just upstream of the pumps) are measured using Omega PX140 sensors, and if this pressure drops to some low value (indicating tube blocking may occur due to ice build-up on the tower), the pump will be shut down automatically. Figure 6 shows the pump control schematic circuit. In addition, the AD12-16 board provides two-channel analog outputs from D/A conversions used for mass flow control. Figure 7 shows the soil temperature measuring circuit and the interface connection to the A/D board.

3.2 CO_2 Analyzer Data

Analog data from the two Li-Cor 6251 CO_2 analyzers (top and middle level) are read by the Keithley Chrom-1 A/D board (Keithley Metrabyte, Taunton, Massachusetts). This high precision voltage measuring board uses a voltage-frequency (V/F) converter and counter to obtain very high resolution and integral accuracy. A resolution of 15 bits is obtained from analog to digital (A/D) conversion when the CO_2 integration interval is set to 0.5 sec. A unique feature is that the board has a +1.0000V calibration reference; through software, the V/F converter can be switched to the signal inputs as well as the reference, providing a means to eliminate any drifts due to temperature or other factors. In addition, the optically isolated input of the board avoids a generation of errors through ground loops. Figure 8 shows the wiring diagram through a 25-pin connector of the board. The third Li-Cor 6251 analyzer data are read by the AD12-16 analog card through the gain programmable multiplexer board (AIM-16). The range of analog input is set to 0-1 V, leading a resolution of 0.24 mV or about 0.2 ppm in CO_2 concentration measurements.

3.3 Valve Control

The two Valco 16-port valves (MPV1 and MPV2 in Figure 1) are controlled by the ACCESS IOD-72 digital board. This board has 72-bit I/O lines and provides user selectable buffered inputs and outputs based on the Intel 8255 PIO chips. Sampling and calibration sequences require random access of the multi-position valves. Through the digital board, the computer writes BCD code to switch valves and reads the valve status lines to obtain position data. Figure 9 shows a wiring diagram between the IOD-72 board and the 16-port valve actuator interface. Table 2 shows the pin assignments of the valve and IOD-72 board connectors. The third valve is a 4-port valve (MPV3 in Figure 1). This valve is controlled by the two relays of the Chrom-1 board. The wiring connection between the 4-port valve and Chrom-1 board is shown in Figure 8.

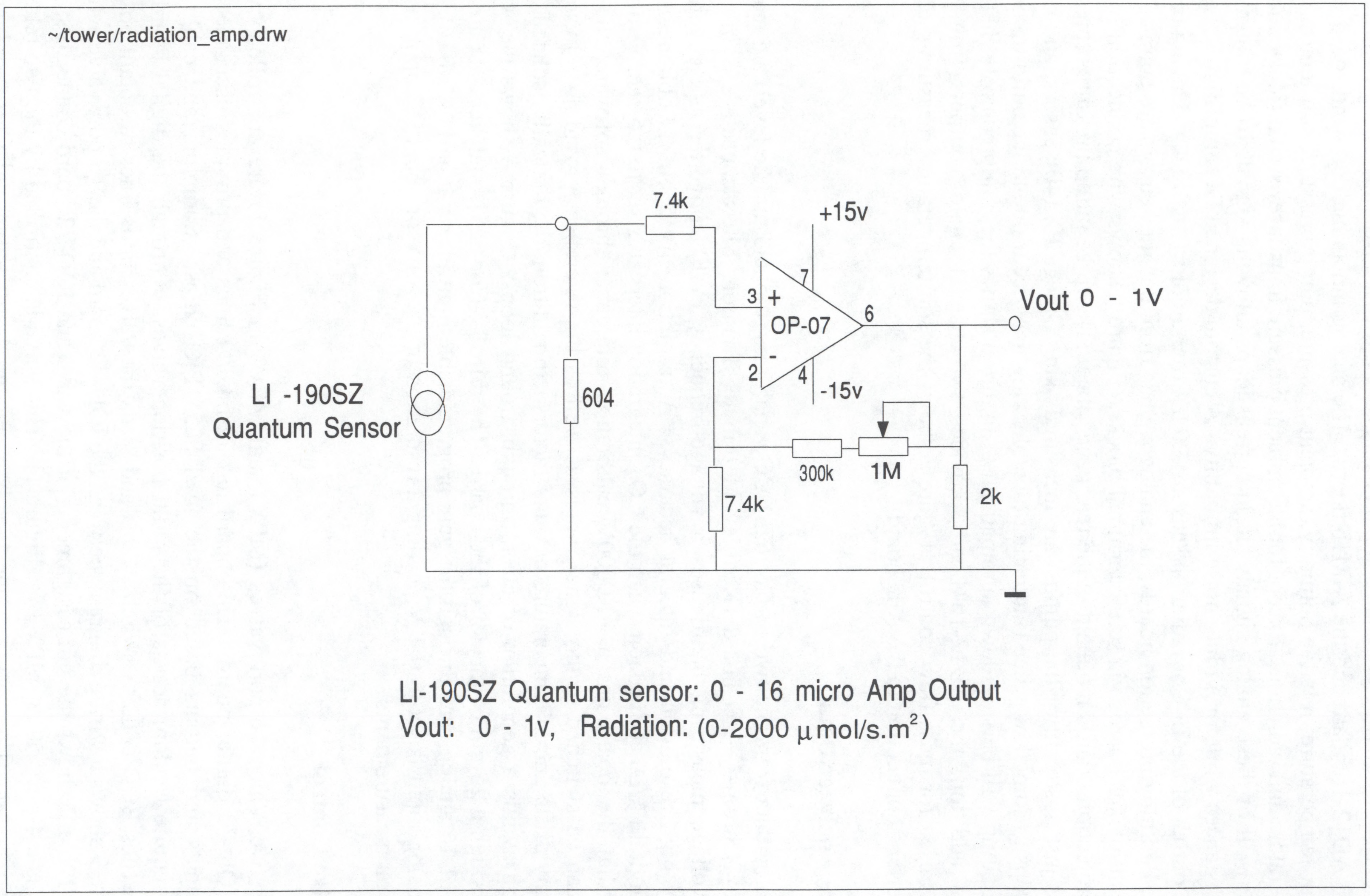
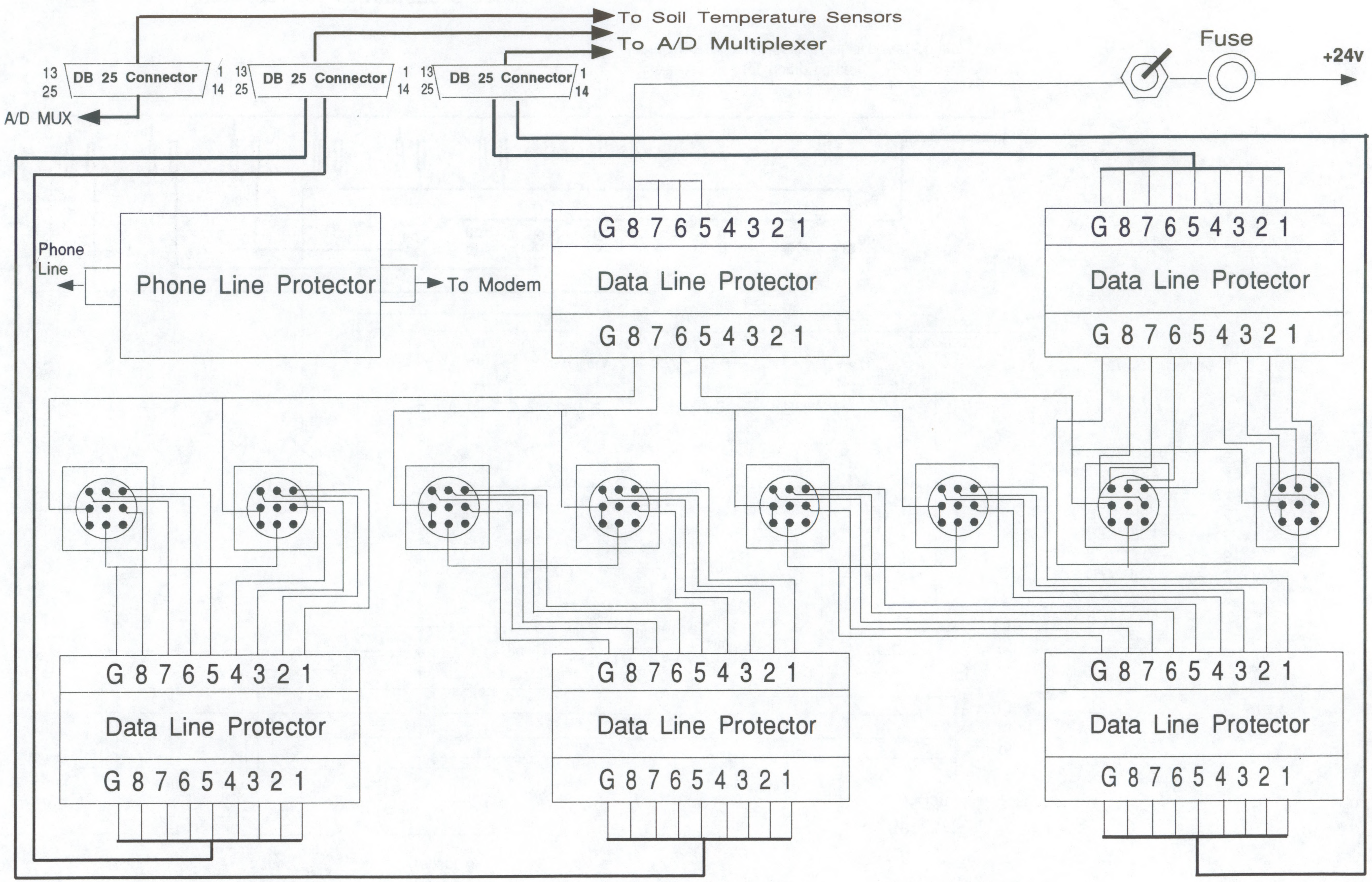


Figure 4. A DC amplifier schematic diagram for the LI-Cor radiation sensor LI-190SZ.



Fogure 5. Wire connection diagram on lightning protector screw teminals

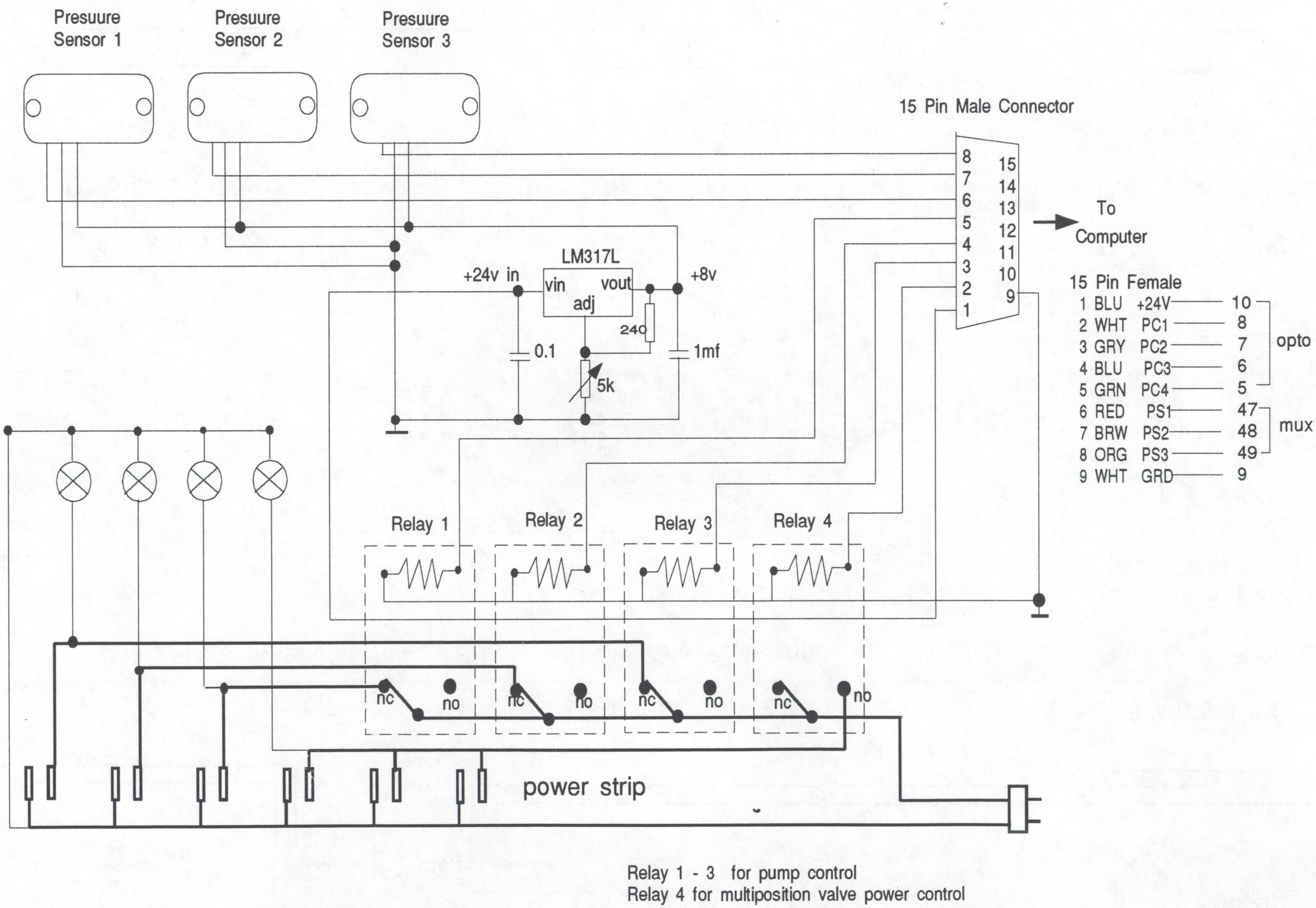


Figure 6. Pump control schematic diagram.

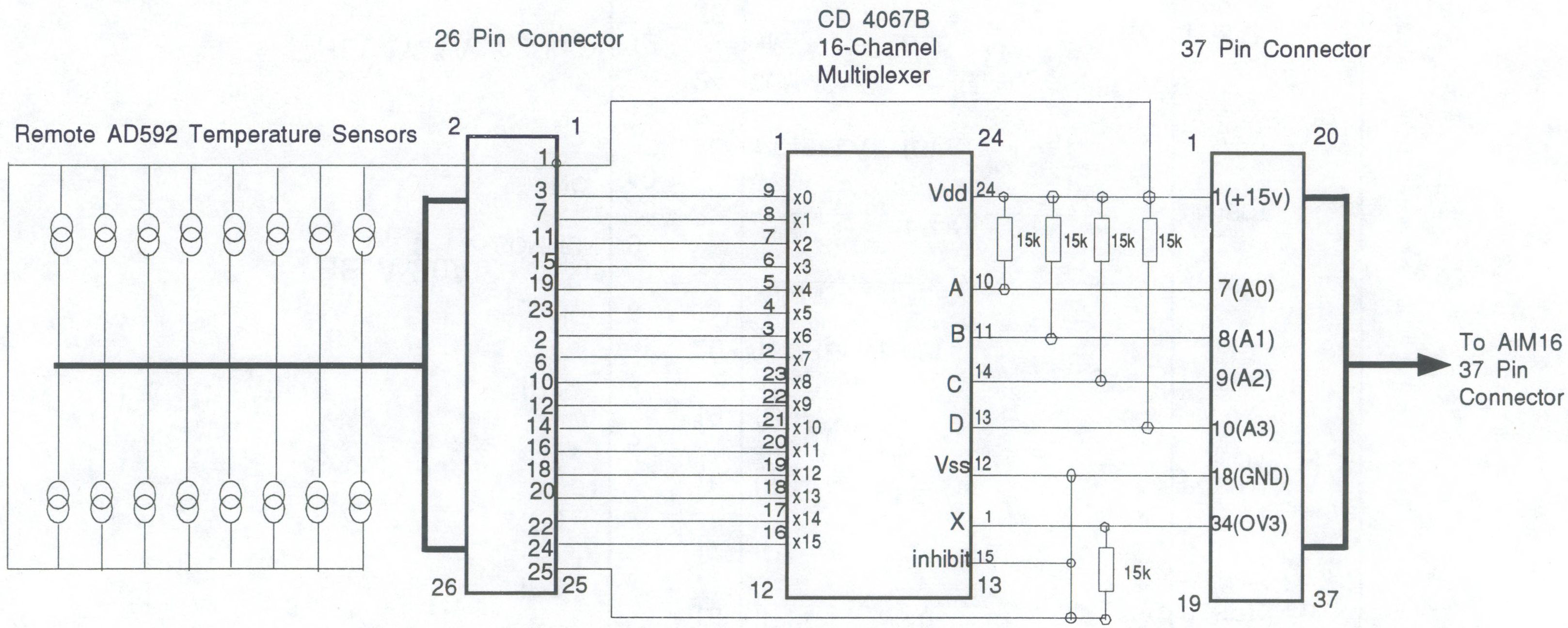


Figure 7. Soil temperature measuring circuit and interface to A/D board.

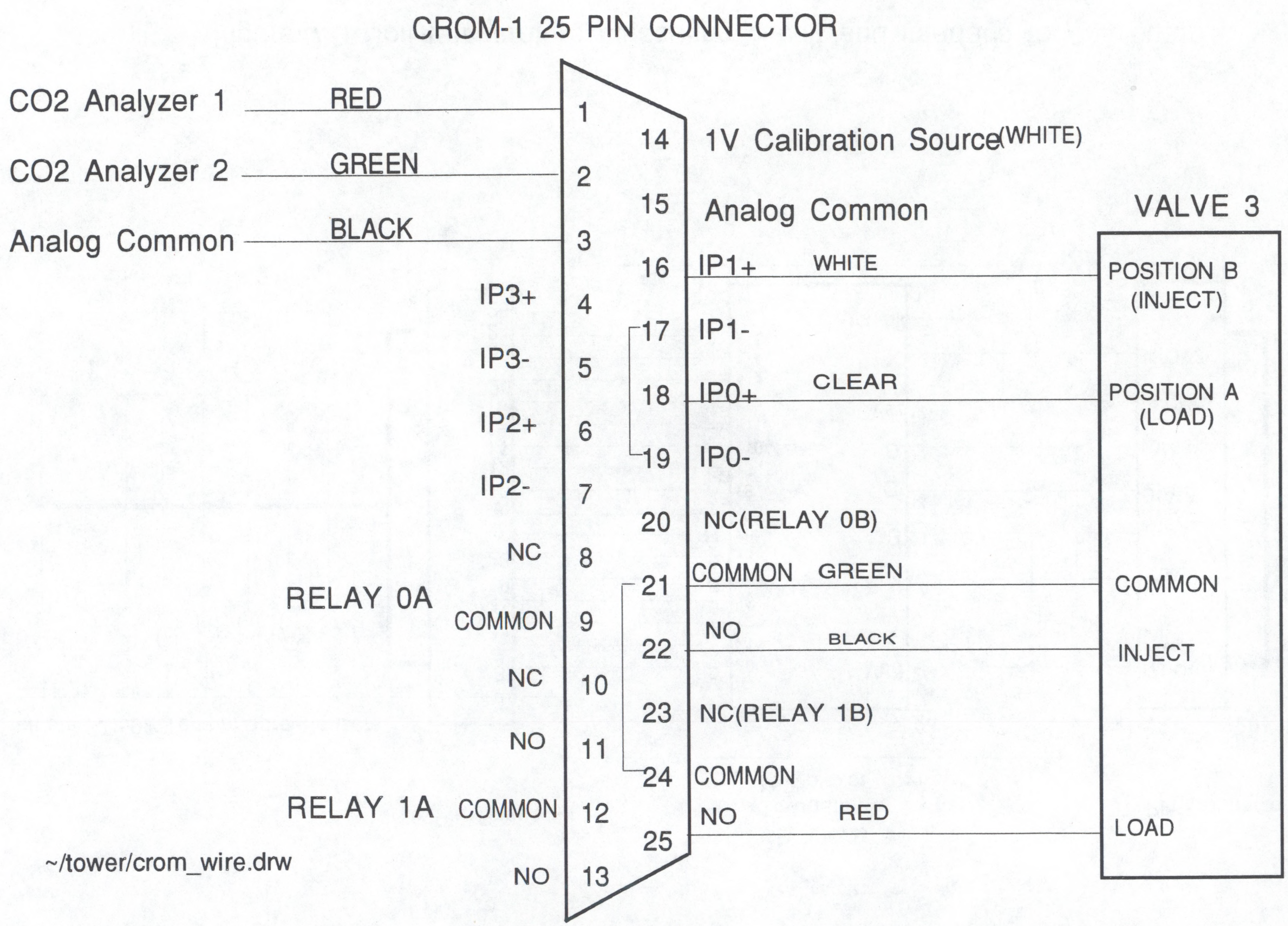
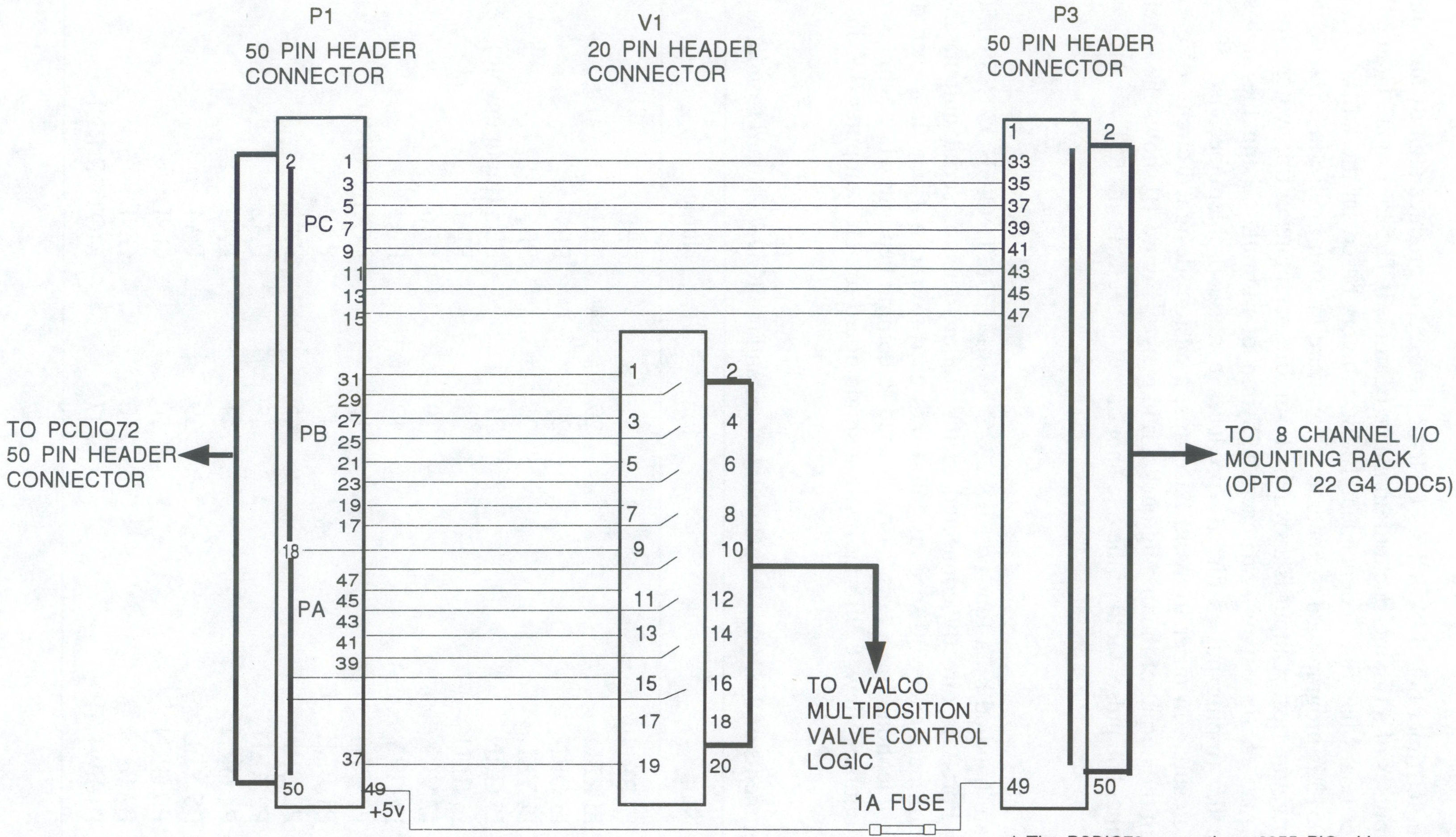


Figure 8. Wire connection diagram of the Crom-1 A/D board.



* The PCDIO72 uses three 8255 PIO chips.
* P1-V1 and P2-V2 have a same wire connection
* 8255 Port To 50 pin Header Connector :
  Port C pin 1 -- 15,
  Port B pin 17 -- 31,
  Port A pin 33 -- 47.

~/tower/pcdio_valco_witn.drw

Figure 9. Wiring diagram between the IOD-72 digital board and the 16-port valve actuator interface.

3.4 Hardware Interrupt and Rain Gauge

A digital counter/timer board (ACCESS CTR-05) is used to produce a hardware interrupt signal and to count pulses of a tipping-bucket rain gauge (Campbell TE525, Logan, Utah 84321). The CTR-05 counter board has five independent 16-bit counters based on the AMD9513 chip. Counter 5 of AMD9513 is programmed to generate a hardware interrupt pulse in 2 Hz, counter 1 is used to count rain gauge tips. Output is a switch closure for each bucket tip; switch closure is approximately 135 ms. A tip occurs with each 0.25 mm of rainfall. Using the high-speed counter to measure the tipping pulses directly produces a noise problem because of a slow mechanical switch closure. In order to avoid false tips, a custom-designed circuit of one-shot pulses is used to trim the output of the tipping bucket rain gauge. Figure 10 shows the schematic diagram of the circuit. The pulse width of the one-shot output is set to 15 ms ($\Delta T = 1.1RC$).

3.5 Serial Data

Serial data are handled by a four-port RS-232C board (COMTROL HOSTESS 550, St. Paul, Minnesota). Port-1 is directly connected to the Radon detector serial output, and the computer reads Radon data every 30 seconds. Port-3 is used to transmit raw data each day to Boulder through the telephone line. Port-2 is dedicated to communications via a wireless radio modem (Proxim, Mountain View, California) with a single board remote computer (OCTAGON

Table 2. Pin Assignments of the Valve Actuator Interface and the IOD-72 Board Connector

Pin	Name	Pin	Name
1	I1 BRN	31	PB0
2	I2 RED	29	PB1
3	I3 ORN	27	PB2
4	I4 YEL	25	PB3
5	I5 GRN	21	PB5 (input enable)
6	I6 BLU	23	PB4
7	I7 VIO (home)	19	PB6
8	I8 GRY (step)	17	PB7
9	I9 WHT	18	LOGIC GND
10	P1 BLK	47	PA0
11	P2 BRN	45	PA1
12	P3 RED	43	PA2
13	P4 ORN	41	PA3
14	P5 YEL	39	PA4
15	P6 GRN	50	GND
16	P7 BLU	50	GND
19	P10 WHT	37	MOTOR RUN

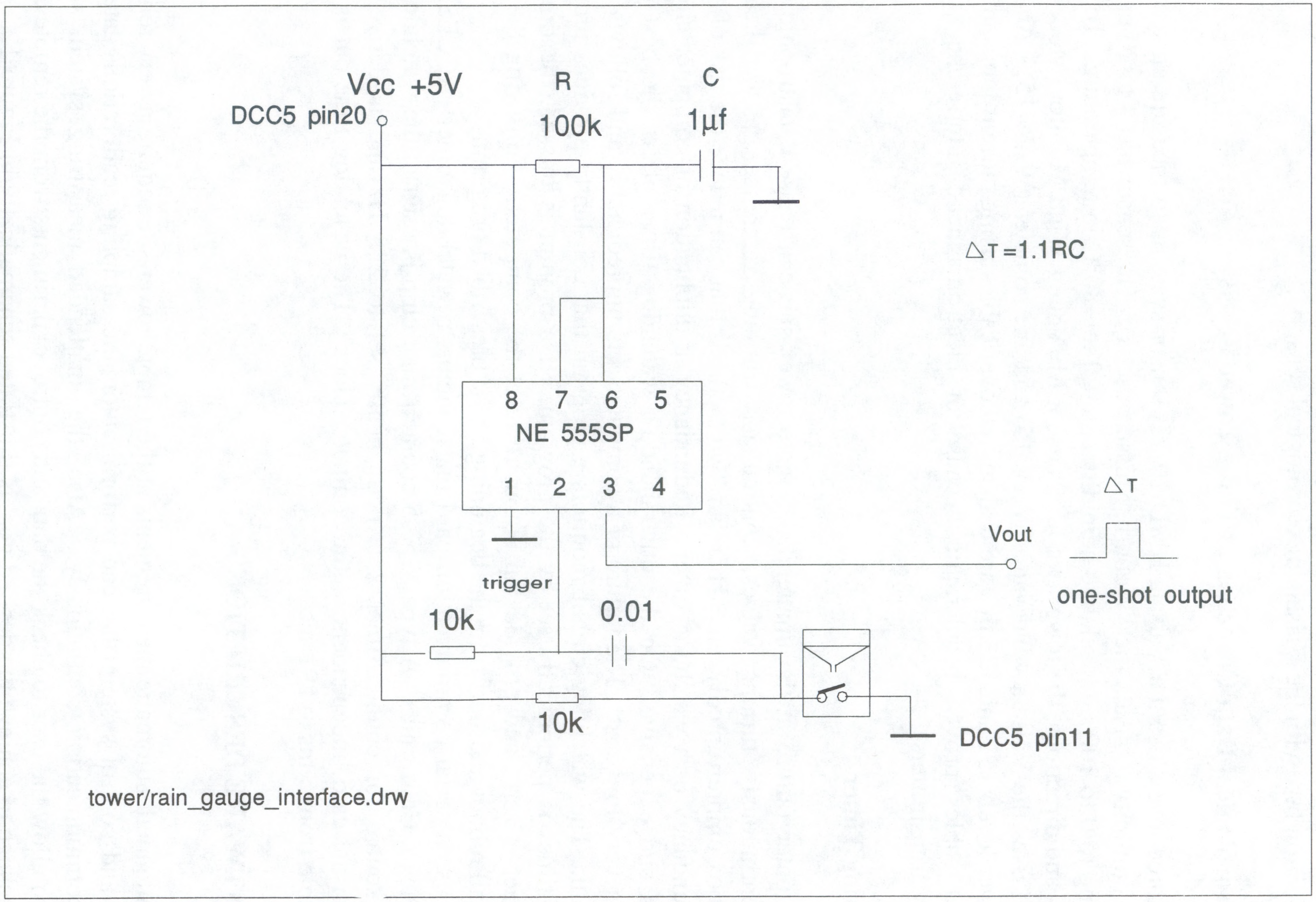


Figure 10. A schematic diagram of circut for counting the rain gauge pulse.

6012, Westminster, Colorado) board computer collects meteorological data continuously at 1 Hz sampling rate and transmits data through the radio modem at 9600 baud rates when it receives a data request command from the base 486 computer. Figure 11 shows the interface diagram of the data collection box with the Vaisala meteorological sensors.

3.6 Meteorological Data Collection at Three Tower Levels

All three levels use the Vaisala HMD 20 YB sensor systems to measure air temperature and relative humidity (Vaisala Inc., Woburn, Massachusetts). The sensor has 4 to 20 mA output corresponding to 0 to 100% in relative humidity and -20 to +80°C in temperature. To measure wind speeds and directions, the lower two levels use R.M. Young Wind Monitor (Model 05106), the top level uses the Vaisala wind vane (WAV 15) and anemometer (WAA 15). Analog data from the lower levels (51 and 123 m) are transmitted over cables using current loops, but for the 496-m level cables proved problematic because of electromagnetic interference from the powerful TV transmitters.

3.7 Watchdog Timer

Computer failure at the unattended remote tower site can cause catastrophic damages such as continuously turning valves, continuously running reference gas, or heating the instrument box uninterruptedly, etc. There are two methods that can reduce the risk of computer failure: redundancy or a watchdog timer. Redundancy, a duplication of computer circuitry, is complicated and expensive. On the other hand, a watchdog timer offers the best available protection at very low cost. The failure of a computer acts unpredictably and follows a strange program path. The watchdog circuit monitors a program that constantly provides prompts. A countdown timer is periodically set by the program. If a prompt is missed, the timer is not updated, reaches zero, and provides an output to reset the computer. Following the rest, the computer will reboot and start from the beginning of the prescribed program.

We use a serial communication card that contains a watchdog timer (ACCESS WDG-SIO, San Diego, California). A type 8253-5 counter/timer chip is used in the watchdog circuit. The clock source for counter/timer 2 is permanently set to 225 Hz and is derived from a oscillator on the card, independent of the computer clock. The watchdog time-out is software programmable from 5 ms to 291 sec.

4. SOFTWARE DESCRIPTION

Unattended, automatic measurements at the remote tower site require a very reliable data acquisition and control system that can perform automatic sampling, calibration, data storage, and data communication continuously. Also, the unattended measuring system should be accessible to allow the user to check the data and control experiments from the remote center. A software package to achieve the desired goal is illustrated schematically in Figure 12. All of the software for the tower measurements except the interrupt handler written in 8086 assembler language, is written in the C programming language. The real-time QNX operating system permits up to 250 concurrent tasks running per computer. It uses a prioritized (16 levels), time

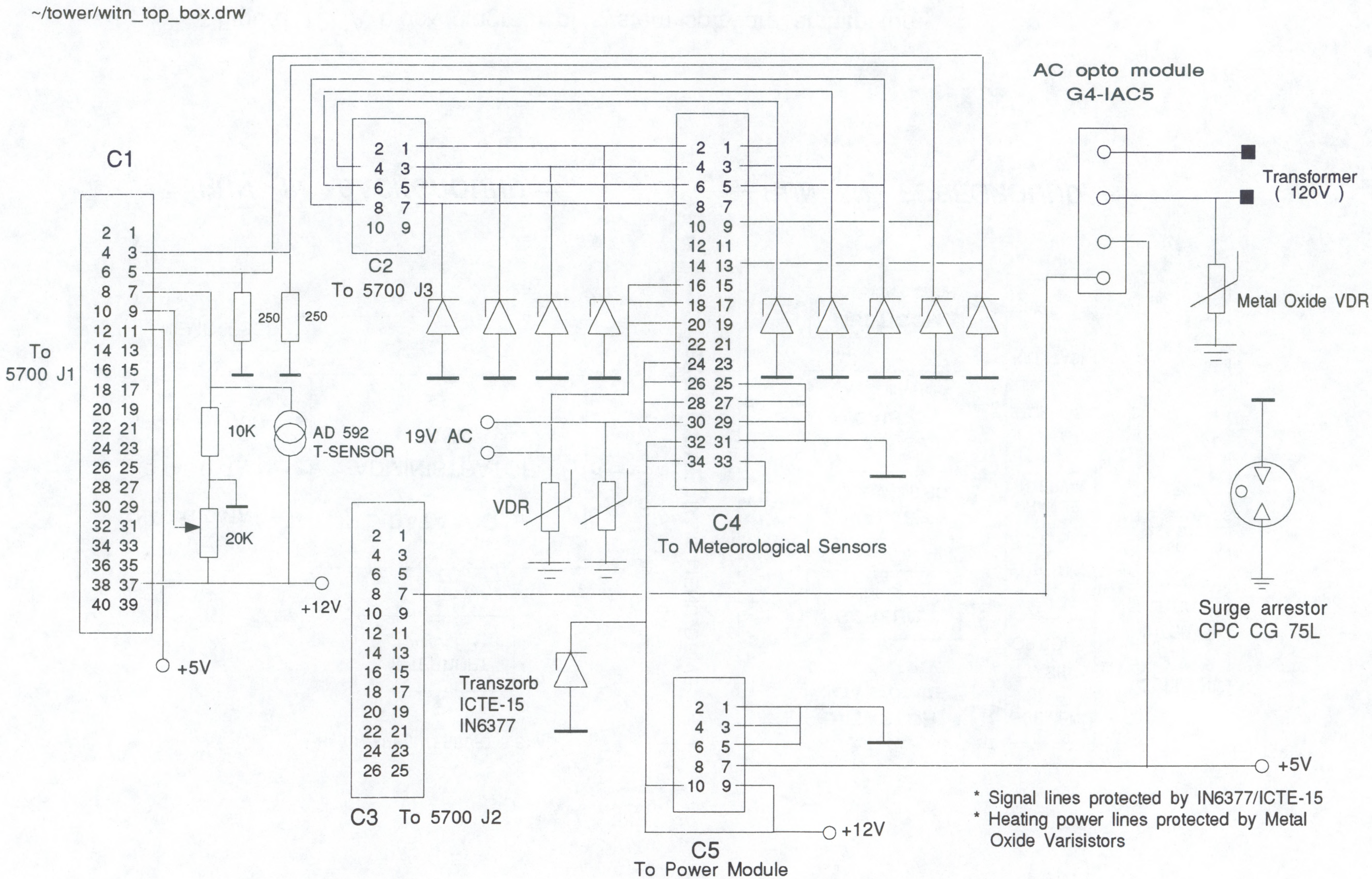


Figure 11. Interface diagram of the data acquisition box located at the top level of the WITN tower.

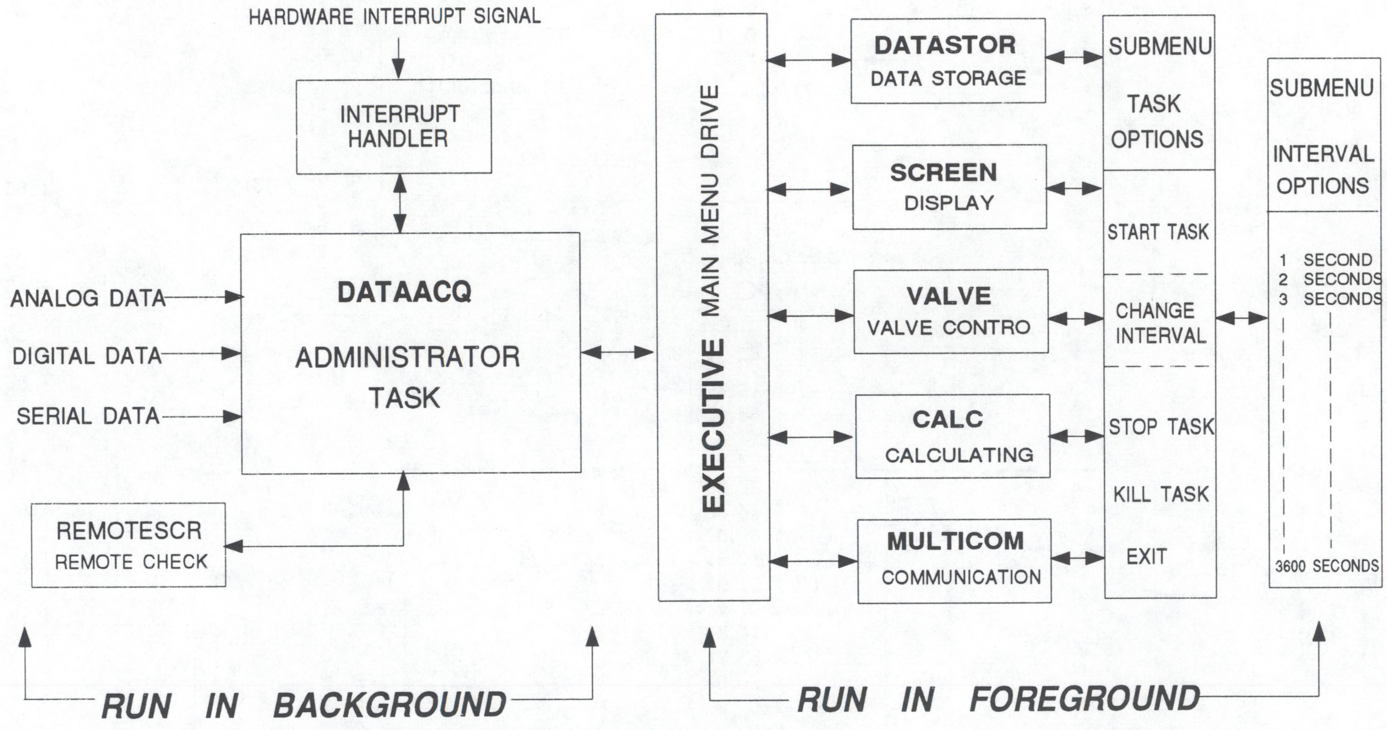


Figure 12. A block diagram of system software architecture

slice scheme with pre-emptive scheduling. Tasks can interrupt each other based on the level of priority assigned by the user. For our tower measurements, there are seven tasks designed to be running continuously for sampling, calculating, storing, valve control, communications, and real-time display.

The main task named DATAACQ is always running in the background with the highest user priority (level 3). This task is written as an Interrupt Administrator with client/server capabilities. An administrator in QNX is a specialized task that controls access to computer resources such as memory, devices, network, etc. Figure 13 shows a simplified flowchart of the DATAACQ program. In an infinite loop, the DATAACQ waits to receive MESSAGES from other tasks and SIGNALS from the interrupt handler. It reads all analog and digital data, and then accumulates sampling data into the separate client buffers while SIGNALS are received from the interrupt handler. As a server, the DATAACQ task will average, calculate variances, and then send data to clients when MESSAGES are received from client tasks. Also, the DATAACQ task can open or close client buffers according to the requirements from the client tasks. The DATAACQ is vital to the measurements since its termination would result in the end of the all application tasks.

The task named EXECUTIVE is the user interface to control application tasks with pop-up menu windows. It starts by initializing variables and reading in an ASCII control table. This table contains various parameters used by the system to set all application tasks. The set parameters include the task on/off option, the running priority, the sample interval, and the display windows. After initializing task parameters, the EXECUTIVE invokes the tasks CALC for data calculations, SCREEN for real-time display, VALVE for CO_2 sample control, MULTICOM for serial communications, and DATASTOR for data storage. Through the pop-up menu, the user can start or stop tasks, change task intervals, modify valve switching sequences, and shutdown the data acquisition process.

There is a special task named REMOTESCR designed to allow remote checks of the data. This is important for an unattended measuring system running continuously at a remote site. Normally the user can log into the tower computer through the modem, and once the login is successful, the user will have a full control of the data system. Running REMOTESCR task will bring the real-time data display windows without interrupting routine processing.

5. DATA PROCESSING AND RESULTS

Figure 14 shows a block diagram of the entire data flow. It consists of three phases: data collection, preprocessing, and data analysis. The data collection step is essentially the hardware-software interface; it obtains various data in digital counts by reading data ports. The preprocessing step involves averaging (we save 30 s averages of all data), calculating variance and covariance, and converting sample counts to raw data in physical units such as CO_2 mixing ratio in micromol mol^{-1}, temperature in Celsius, and wind speed in m sec^{-1}, etc. During preprocessing, the calibration information is extracted and used to convert the data. A common data compression software package has been implemented for the purpose of reducing raw data size. This customized software allows us to retrieve the compressed data file directly in various platforms such as QNX, DOS, and UNIX. The program uses a dictionary-window technique to achieve compression [*Ziv and Lempel*, 1977], it can typically reduce raw data size by 70% to 90%. Data analysis is discussed in detail in a separate paper [*Bakwin et al.*, 1995].

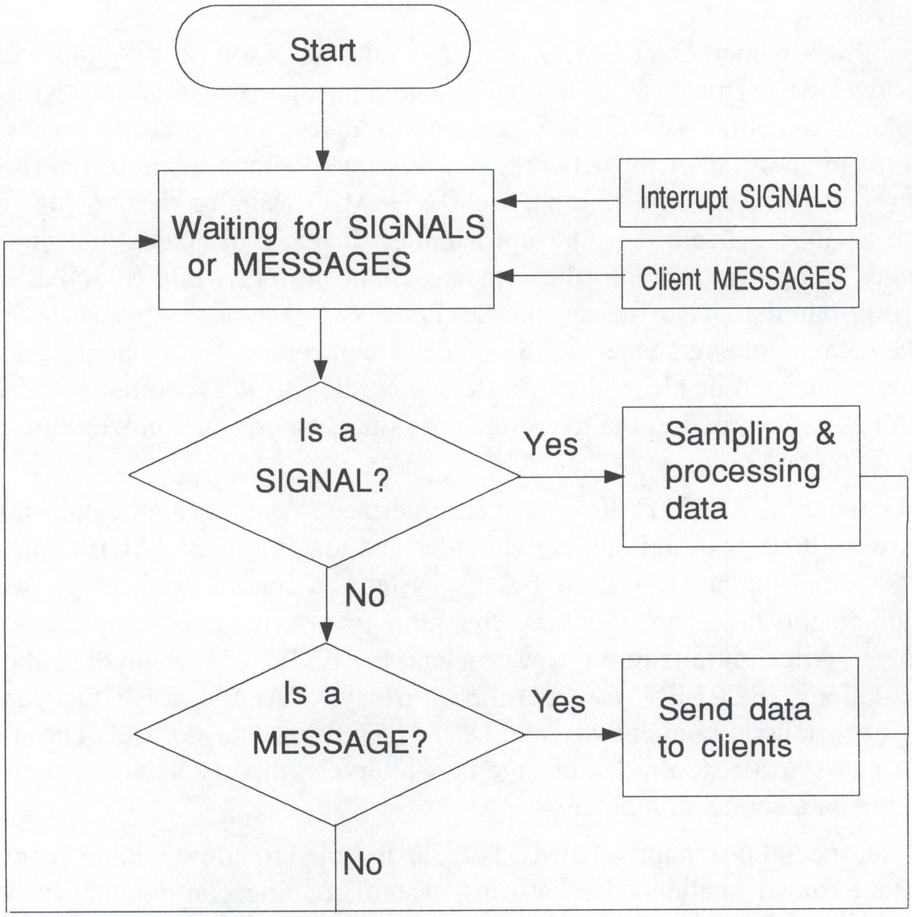


Figure 13. A simplified flowchart of the administrator task named DATAACQ.

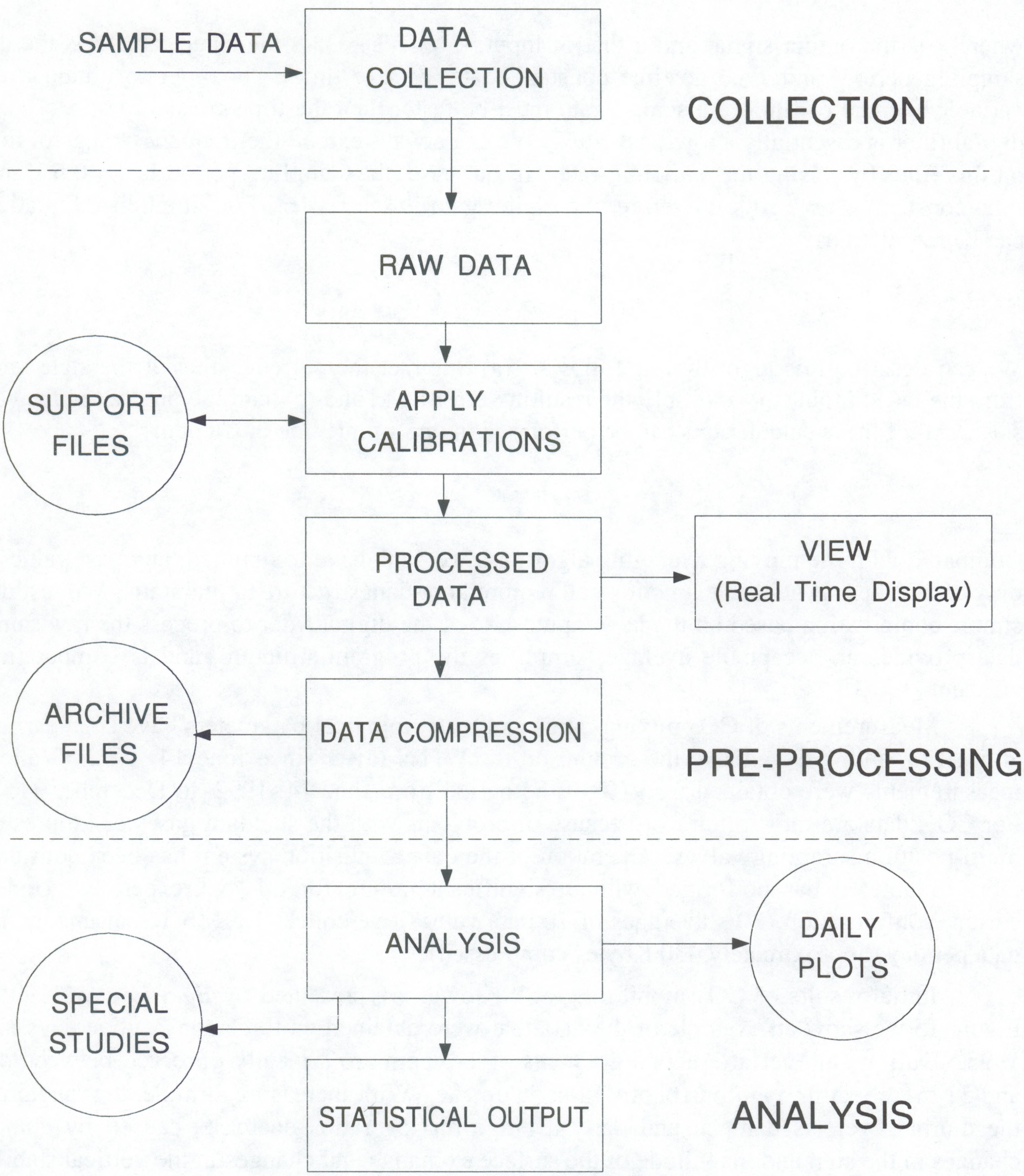


Figure 14. An overview of data flow scheme.

To process the raw sample data in real-time, we use an exponential digital filter to obtain variable averages. The algorithm can be written in the following equation [*Peled et al.*, 1976]:

$$x_n = ku_n + (1-k)\, x_{n-1} \qquad (1)$$

where x is the output signal and u that of input, $k = T/(T+\tau)$, is the filter gain, T is the digital sampling period, and τ is the time constant (data average time). In order to obtain a useful variable average of filter, the sample rate must be faster then the time constant ($\tau/T >> 1$). The digital filter is essentially a low-pass filter. We can always extend the frequency range of interest on this filter by raising the sampling rate. In our case, the sampling period is T= 0.5 s and the time constant is τ = 30 s; therefore, the digital gain is k = 0.016. For simplicity, Equation (1) can be rewritten as:

$$x_n = x_{n-1} + k\,(u_n - x_{n-1}) \qquad (2)$$

We can describe this algorithm as follows: (a) Subtract the current value of the state variable from the latest input, (b) multiply the resulting error by k, and (c) add the product to the current state. All of these calculations can be performed in one simple line of C code:

```
x + = k * (u - x).
```

Compared with the moving averaging algorithm, we don't have to maintain any past values of u, only of x. There is neither a function call required nor data structure to maintain. We just do one simple computation based on the new input. Use of the digital filter to process the raw sampling data provides an acceptable average, simplifies the program structure, and is computationally efficient.

Measurements of CO_2 mixing ratios and meteorological parameters have been carried out at 51, 123, and 496 m above the ground on the WITN tower since June 14, 1992. Valid CO_2 measurements were obtained for 91% of the period from June 14, 1992, to December 31, 1996. For CO_2, data are most often lost because of problems with the standard gases or failures of the multi-position sampling valves. Operation of the data acquisition system has been considerably more reliable; it has performed without significant failure for this entire period. Under the current configuration (30 s averages of 70 data values) we collect 1.6 Mbytes of uncompressed data per day (approximately 430 Kbytes compressed).

Initial results of CO_2 monitoring at the tower are presented by *Bakwin et al.*[1995]. In Figure 15 we show an example of the data that were obtained on three consecutive days in June 1993. During summer afternoons gradients of 1-2 ppm are typically observed between 496 m and 51 m, reflecting vigorous photosynthetic uptake. With increasing altitude, the magnitude of the diurnal cycle is damped and daily average mixing ratios decrease, caused by coincident changes in the sign and magnitude of the surface exchange and changes in the vertical stability of the atmospheric boundary layer over the course of the day [*Bakwin et al.*, 1995]. The amplitude of the seasonal cycle at 496 m (not shown) is larger than at marine boundary layer sites at nearly the same latitude, such as Bermuda [e.g., *Conway et al.*, 1994]. Comparison of our continental tower data with data from background sites should provide a strong constraint for regional and global models of terrestrial CO_2 fluxes *Fung et al.*, 1987. In addition, the vertical profile

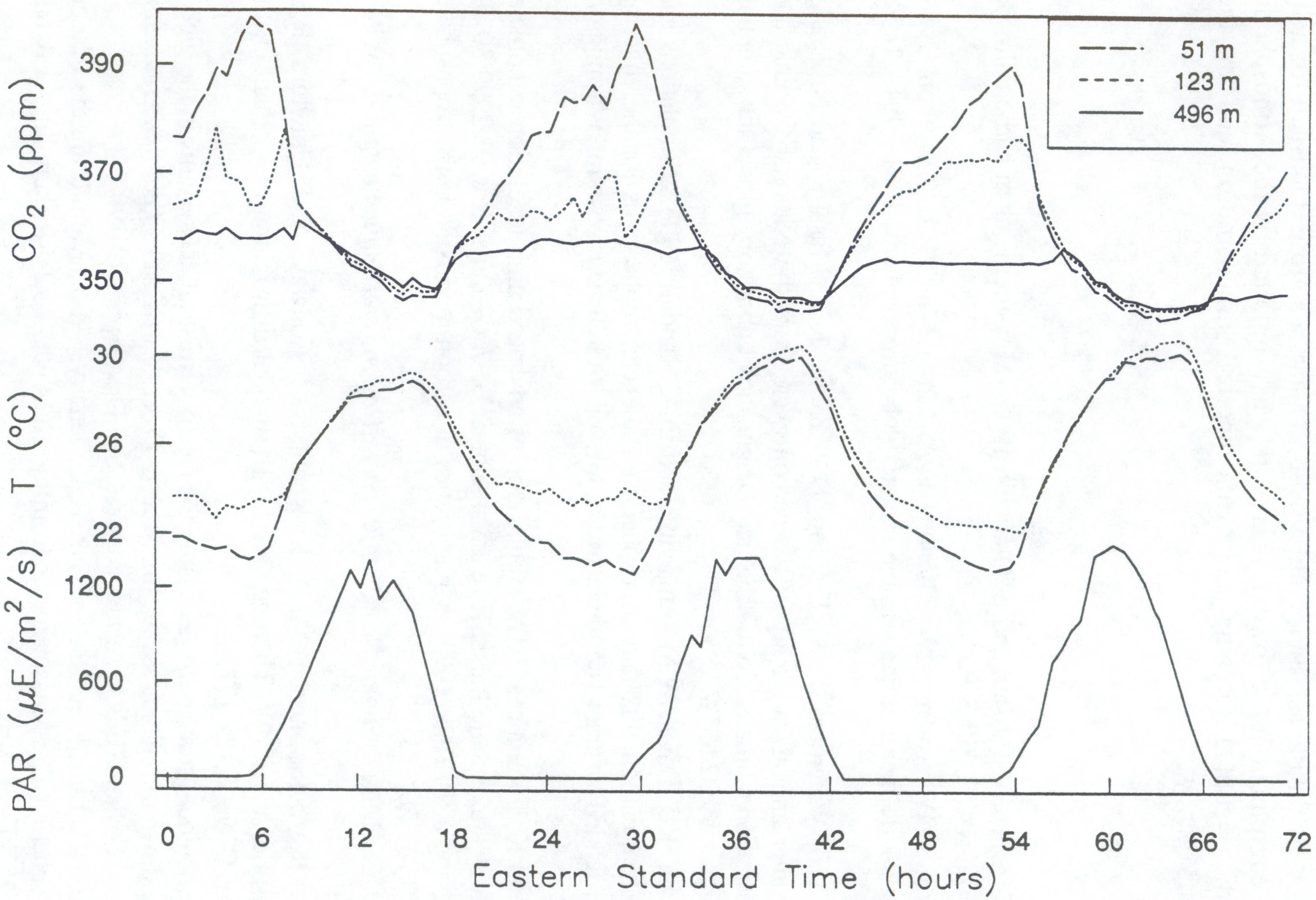


Figure 15. Three days of CO_2, temperature, and photosythetically active radiation data in June 1993.

measurements up to 500 m above the ground provide data to test parameterization of boundary layer mixing and surface exchange within models [e.g., *Denning et al.*, 1996].

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