Control and Monitoring Instrumentation for the Continuous Measurement of Atmospheric CO_2 and Meteorological Variables

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ABSTRACT

The NOAA/GMCC program was chartered to monitor the trends in those atmospheric constituents that can cause climate change. A four-observatory network was established, and a 15-year database has resulted for selected variables. At the inception, a central data-recording system was established at each observatory using minicomputers to compress and record the signals from monitoring instrumentation onto a computer-compatible magnetic tape. A distributed recording system using Z80 microprocessors has recently been developed to replace the minicomputer system. The STD BUS was selected as a means of internal computer communication, thus allowing a modular design that was tailored to the specific instrumentation. The resulting Control And Monitoring System (CAMS) operates an interactive multitasking version of FORTH as the operating system software. Separate versions of CAMS were built to control and monitor the carbon dioxide analyzer, aerosol and solar radiation instrumentation, and meteorological and surface ozone instrumentation. Subsequently, 20 CAMS were assembled and tested and deployed at the observatories. Early results show that CAMS recovers very well from power outages, resulting in minimum data losses. Furthermore, by distributing the system, it has been possible to reduce significantly electromagnetic noise pickup at the input. The quality of the recorded data is significantly improved in comparison with open-reel, computer-compatible tapes. All factors have contributed to better data quality.

1. Introduction

The growth in concentration of trace constituents in the atmosphere due to anthropogenic activity is well documented. Their subsequent potential for causing climate change through redistribution of radiation is now under intense study. The Geophysical Monitoring for Climatic Change (GMCC) program, a division of the Air Resources Laboratory, Environmental Research Laboratories, NOAA, was formed in 1971 to monitor those atmospheric constituents such as CO_2, aerosols, and ozone. At that time, measurements of these and other variables were being made at the Mauna Loa Observatory (MLO) in Hawaii and at the South Pole Station (SPO) in cooperation with the National Science Foundation. Both sites are at an altitude slightly in excess of 3 km. Two sea level stations were subsequently constructed at Barrow, Alaska (BRW), and on Tutuila Island in American Samoa (SMO). At each station there were more than 20 continuously operating sensors requiring recording and subsequent processing for trend analysis. At this time, the instrumentation consists of condensation nucleus counters for measuring aerosol samples; nephelometers for measuring wind, pressure, temperature, humidity and analyzers for measuring carbon dioxide concentration; Dasibi ozone meter for in situ measuring of ozone concentration; standard meteorological instruments for measuring wind, pressure, temperature, humidity, and precipitation; pyranometers and pyrheliometers for measuring solar radiation and atmospheric turbidity. These sensors and the resulting data are discussed in an annual series of GMCC Summary Reports. [See Harris and Nickerson (1984) for the most recent status report.]

When GMCC was organized, most of the data were recorded on strip chart recorders. Processing such data was a long, arduous task. At that time both the number of stations and the number of sensors were planned to double. To facilitate the processing and analysis of these many and varied signals, a minicomputer-controlled

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data acquisition system was built that would record the data on a computer-compatible magnetic tape. The system also provided control signals to operate the solenoids that switched reference gases through the infrared analyzer that monitors atmospheric CO_2 (for calibration purposes). This system became known as the Instrumentation Control and Data Acquisition System (ICDAS) (see Herbert et al., 1980). ICDAS consisted of a Data General Nova minicomputer with a factory-interfaced nine-track NRZI tape drive. A teleprinter was used to control the system. Customized interfaces were developed to provide analog signal acquisition and digital signal control and to interface a battery-backed clock calendar. ICDAS was designed with mid-to-late 1960 technology. For this reason, the supply of spare parts for those components using diode-transistor logic became scarce. By 1980, maintenance and repair costs were rising at an alarming rate.

The long-term monitoring of trace constituents in the atmosphere places a different set of demands on design of instrumentation control and monitoring equipment than is common in the typical laboratory environment. Reliability and ease of repair become important considerations. In the typical laboratory environment, if a problem is detected, it is often possible to call in a repair service. This is not an option at sites such as Antarctica or Samoa. The equipment must be designed such that the resident technician can make changes or repairs when necessary. A modular design is called for so that problem components can be identified. This was one of the major failings in the design of ICDAS. In terms of both hardware and software, it was a highly integrated system, and problems were, therefore, often difficult to isolate. The system must also provide reasonable noise rejection and quick recovery from power outages for a continuous data stream. Most minicomputer systems, such as ICDAS, require operator intervention to recover magnetic tape operation after a power outage. For this reason, a momentary interruption in power could cause an extensive data loss if the observer was unaware of the failure. Another factor that leads to reliable data is a systematic procedure by which the observers can evaluate data quality in real time. This requires that the instrumentation displays the necessary statistics and information to facilitate such determinations. In the period of ICDAS, such determinations were usually based upon visual observation of strip chart recordings. In some cases ICDAS computed hourly average values in scientific units, but such values were only available for the previous hour because it was not possible to recover data from the magnetic tape while the system was operating. This limitation made data quality assurance a once-a-day spot check function. It was not until a listing of the tape record was returned to the station 8 to 10 weeks later that the staff could review the entire dataset.

In this paper we describe the development and testing of an instrumentation control and monitoring system to meet the needs of the varied instrumentation at the GMCC observatories. A microprocessor-controlled gas switching device was the first prototype to this system (see Harris et al., 1980). The system is designed first of all to improve the reliability of data recording over its predecessor, ICDAS. It is, therefore, designed from modular units as much as possible. Second, it is designed to provide, on request, a complete listing of all the stored and recorded data and meaningful data quality assurance on a daily time scale. These goals were realized by distributing the processing. We first discuss the hardware composition and then the software that is tailored to each application. A brief discussion of the results concludes the paper.

2. Instrumentation

The principal design requirement for replacement hardware for ICDAS was increased reliability through the use of a simplified, low-cost tape recorder, erasable programmable read-only memory (EPROMs) for program storage, and a built-in autorestart capability to resume operation after a power outage. The recently proposed standard bus (STD BUS) was adapted as the best means of internal data communication because of the wide variety of peripheral interface options available from different vendors. The STD BUS is an eight-bit microprocessor bus standard in which small card size (165 mm × 114 mm) in conjunction with large-scale integration (LSI) semiconductor technology provide a module-per-function design approach. The standard is maintained by the STD Manufacturer's Group (1985). The most complete listing of STD-BUS-compatible modules and pertinent specifications can be found in Mazanec (1984).

The ICDAS replacement has been labeled the Interactive Instrumentation Control And Monitoring System referred to simply as CAMS. The basic CAMS consists of a central processing unit (Z-80 microprocessor); read-only memory (EPROMs containing the software); random access memory (8000 words, battery powered); serial input/output interface (dual channel, RS-232C); clock/calendar (battery powered); digital input/output (16 channels); and an analog-to-digital converter with power supply. For the specific requirements for carbon dioxide measurements, in addition to the above, it is also necessary to have digital input and output to control gas flow to the analyzer. See Fig. 1 for the STD BUS interface for the CO_2 CAMS.

Each major function is represented by a separate board. Two boards are required to supply the needed random access memory (RAM) and serial input/output (I/O) ports. In other applications an RS-422 interface is required and, where digital control is not required, the digital input/output card is deleted. Depending upon the number of the devices supplying voltages, the analog-to-digital converter is configured in either a single ended or differential input configuration. In all cases

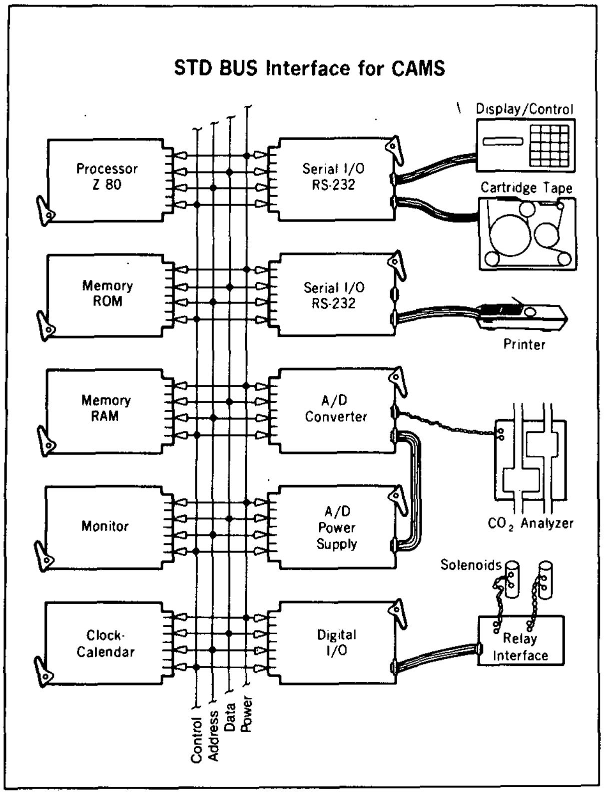

FIG. 1. Block diagram representing the STD BUS showing the interfaces required for the CO_2 CAMS.

the input is scaled for a 0 to 10 V range with a resolution of 2.44 mV per bit. The card cage that configures the STD BUS, and all other components of CAMS, is shown in Fig. 2. All components of CAMS are housed in a rack-mounted crate (48.3 cm × 17.8 cm × 55.9 cm), as shown in Fig. 3.

A cartridge-type magnetic tape recorder is a reliable and relatively inexpensive means of recording data, if the volume is not excessive. In this application it is possible to distribute the sensors among several CAMS and compress the data to obtain reasonable recording durations of 2 to 4 weeks on a single cartridge. The cartridges are preformatted into 512 blocks, each of which holds 512 eight-bit bytes, thus yielding a tape capacity of more than 262 000 bytes. All data are recorded in binary. A panel containing a numeric and function pad is used to control the operation of CAMS. Each peripheral device and calibration operation is assigned to a unique function switch. The panel provides eight switches for this purpose. A display, which is part of the panel, is used to monitor the operation of the CAMS. The display panel and tape drives are pictured in Fig. 2. A standard 80-column printer, of the type commonly used with personal computers, is used to list the data files, and a switch is provided so the printer can be shared by more than one CAMS. The tape recorders, display/control panel, and printer communicate with the STD BUS through three RS-232 ports. The clock/calendar is contained on a separate board and accesses the BUS directly. The clock is powered by a battery that provides a 5-day life through a power outage.

Although the cartridge tape unit is designed to operate much as a disk, with individually numbered blocks, access times are significantly longer when the blocks are recorded sequentially. Therefore, for ease in recording and subsequent access, the blocks are recorded in logical order, thus minimizing search times. By supplying extra RAM it is also possible to store data

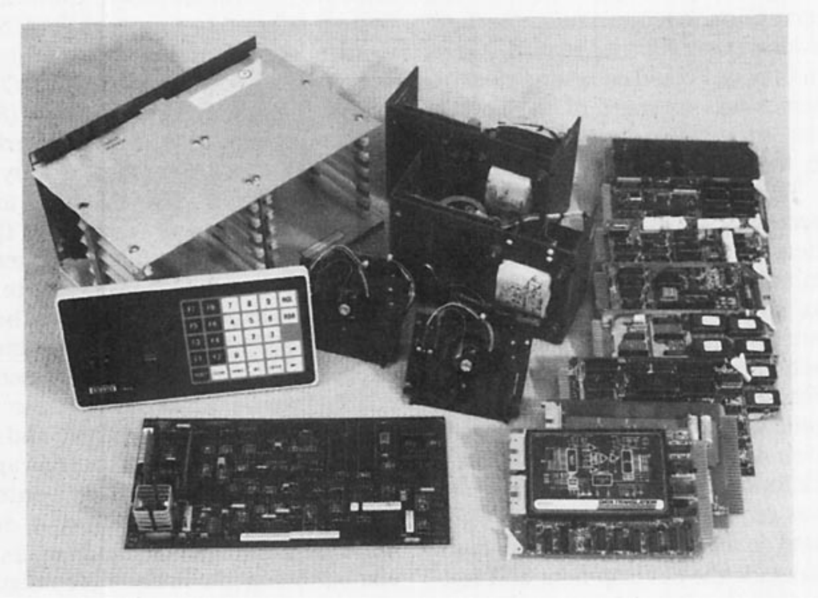

FIG. 2. The components that make up CAMS.

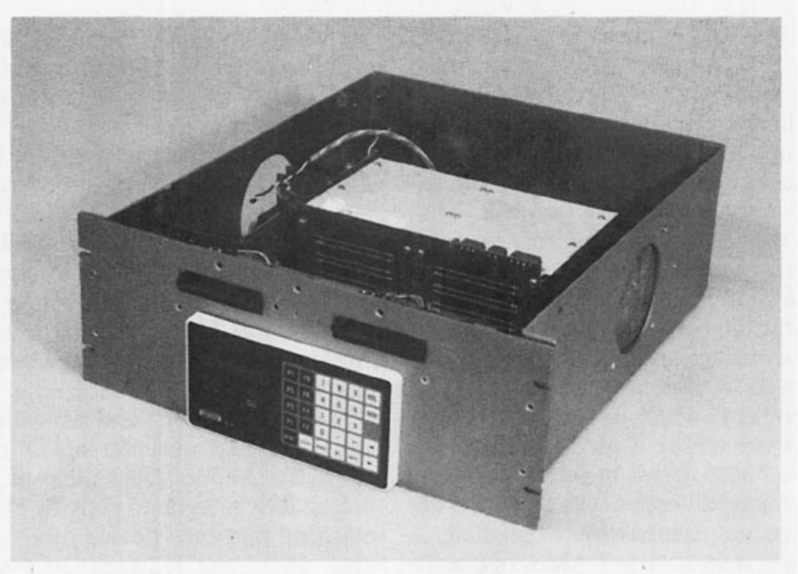

FIG. 3. The CAMS hardware with the top removed.

in logical order and to record those data on individual blocks. In this way the hourly average values for an entire day can be accessed by acquiring the contents of a single block of tape. This facility speeds data access and retrieval. Higher resolution data or calibration values can be skipped if not needed.

Reliable computer-aided instrumentation that is designed for continuous operation is ensured through the use of carefully designed and thoroughly tested software. Because of its basic structure, which consists of a collection of functional modules represented by words, the language FORTH was chosen as the operating system for CAMS.[1] By its very nature it supports modular design, which in the long term greatly facilitates testing. (See Brodie, 1981.) Its suitability for microprocessor applications rests primarily with its minimal overhead, which yields an extremely compact code that compiles into space roughly equivalent to that required by assembly language programs and runs at approximately the same rate. Speed is of utmost importance in continuously operating multitasking systems, such as CAMS. The use of FORTH also facilitates extensibility by providing a minimum set of constructs that can be used to build any new construct such as a data structure (Harris, 1980). This aspect of FORTH's structure is consistent with the requirements for transformation suggested by Enke (1982). The version of FORTH used in CAMS was purchased from Microsystems, Inc., of Pasadena, CA.[2] Software was developed on a Tektronix 8002A microprocessor development system.

Dedicated real-time applications add a new dimension to microprocessor systems such as CAMS. There is a need to support concurrent operations, usually involving data input and output processes that need to be handled in a rapidly interleaved, time-shared manner. In CAMS such needs arise when signal acquisition and digital conversion must occur independently and asynchronously and when data output to the tape unit or printer must occur simultaneously. This situation is frequently handled by use of a combination of interrupt-driven processes in the foreground while slower operations are relegated to the background. This method fails when lengthy processes in the foreground block interrupts from lower priority tasks for too long. The background program often takes the form of a loop that performs each function assigned to it in order. As the loop becomes too big, it is often necessary to subdivide these functions into smaller routines and to interleave their execution, to share the processor between them and to obtain a reasonable appearance of a time-shared operation. The multitasking system used on the CAMS, RTOS-80Z (Microsystems, Inc., Pasadena, CA), provides an organization to background program management. RTOS-80Z is compatible with the FORTH compiler.

The multitasking control system (MTCS) handles CAMS operations as a number of tasks with a priority assigned to each task. Although tasks are generally separate program entities that are intended to execute independently, they can share common resources such as peripherals and data structures and can communicate with one another. The MTCS scheduler is activated by an interrupt from the CAMS hardware at 10 ms intervals, at which time it examines the priority of the task currently running to verify that a higher priority task is not ready and waiting. From the running state, a task can exit to a suspended state where con-

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[1] FORTH is the unusual, high-level language developed by Charles Moore for instrumentation control applications.

[2] Trade names and company names are included for the benefit of the reader and do not imply a specific endorsement of the company by the NOAA, Environmental Research Laboratories.

ditions for rescheduling to a ready state are assigned; or the task can exit to a dormant state, where it will stay until a start command is issued by the background program to move the task to a state of ready. When the time-slice interrupts the MTCS scheduler, it stops the running task, places it in the ready queue, and examines the queue for the highest priority task. That task becomes the running task for the next interval. The MTCS supplies a number of commands and service calls for starting, stopping, and resuming task execution. Communication between the tasks can be carried out using event flags and semaphores. When two or more tasks need to share a common resource, in this case a peripheral device such as the tape recorder, display, or printer, a semaphore is used to control access. The semaphore limits access to selected devices in a "first-come, first-served" order. The MTCS is designed to be as transparent to interrupts as possible. A Z-80 microprocessor system such as CAMS, operating at 2.5 MHz, adds less than 160 μs to the interrupt routine's execution time.

CAMS is operated through a set of function keys on the display/control module. The function keys are in two rows in the center of the display/control module, labeled F1 through F8. (See Fig. 3.) The keys are assigned in the following order: F1 is assigned to the calendar/clock, providing a reset function. F2 displays the readings of the analog-to-digital converter. Voltages can be displayed in terms of bits or their millivolt values. F3 controls the operation of the magnetic tape recorders. The function includes operations to check the performance of a tape cartridge before recording and/or the orderly changing of tapes. The fourth function key, F4, is used to send data to the printer. F5 is a system function that allows the operator to investigate the cause of an "auto restart." This message appears on the display after every restart. F5 is also used to clear the message from the display. The next two functions, F6 and F7, are used to control the processing of data. The first allows the insertion of calibration and related factors into the CAMS. The second provides for the activation of calibration functions. F8 provides a directed start/restart sequence for those situations when battery-backed RAM fails.

On the basis of a very preliminary set of requirements that was established from experience with ICDAS as a starting point, a basic set of module requirements was formulated. Using a microprocessor development laboratory and the associated emulator package, we tested and evaluated selected STD BUS compatible boards. These included battery-backed RAM and clocks, digital I/O, and RS-232 modules from different vendors. By April 1982 a very preliminary prototype unit was assembled and operational. By September of that same year two additional prototype units were operational. Later in the year one was sent to MLO to serve as a data acquisition system for a set of research instrumentation that measured solar irradiance. This system contained all the I/O functions planned for CAMS except printout and used an interrupt-driven version of FORTRAN as a compiler. Through experience with this unit, it was determined that FORTRAN was too slow to operate interactively for GMCC applications. The FORTH compiler for the development laboratory was acquired in December 1982, and the multitasking software was acquired in June 1983. Because of the success of the MLO solar radiation instrument, it was decided to conduct an evaluation of the analog-to-digital converter. Using FORTH, a second instrument was programmed to record voltage levels and compute first- and second-order statistics. This project was initiated at MLO in July 1983 and ran with minimum difficulty until the power was interrupted by a lava flow in April 1984. By October 1983 the multitasking routine was successfully integrated with the FORTH programs and machine language device drivers. By the end of the year, 16 of the required 20 CAMS had been constructed. A floating-point software package was procured to facilitate the computation of second-order fits required by the CO_2 analysis. In March 1984 it was determined that to obtain a reliable restart after a power outage, an internal restart had to be issued after the power stabilized. The detection of stable power and the issuance of the interrupt signal was designed onto a separate board known as a "monitor board." It was designed in-house, and 20 were assembled by June 1984. Software testing for all three units was completed in May. A sequence was begun whereby the three specific units for each station were tested for a 6-week period before shipping. Once shipped, the next set of three was put in the test sequence. The BRW CAMS units were installed in August 1984 (Fig. 4), SMO in October 1984, SPO and MLO in November 1984. Because of shipping requirements, the SPO CAMS was tested earlier in the year.

3. Signal processing

For the most part at the GMCC observatories, the spectrum of variations in the signals to be recorded is decreasing rapidly at frequencies of 0.1 Hz or greater. In particular, the nondispersive infrared analyzer has a frequency response of about 0.05 Hz. With increasing frequencies the next major noise source is at 60 Hz. To limit the influence of 60 Hz noise, a five-point digital filter was built into the subroutine that operates the analog-to-digital converter. This was accomplished by averaging five readings of the A/D converter spaced approximately 33 ms apart such that in one 60 Hz period an average consisting of five different portions of the sine wave are included. Readings are made at 1-s intervals. All input signals are subsequently checked against expected extreme values that are supplied by the operator. Windowing such as this rejects the transients that frequently occur on the power lines in remote locations. Further smoothing of the data is ac-

FIG. 4. Two CAMS shown at the top of the equipment racks in a typical installation. The printer that is shared by the three CAMS is located in the middle of the right-hand rack. The RS-232 switch used to select the individual CAMS is located immediately above the printer.

complished by forming 1-min average values of the voltage for display purposes. The display/control panel on CAMS automatically displays the latest 1-min voltage. Such values are scaled using calibration factors determined by analyzer calibrations performed hourly, using a set of reference gases.

The CO_2 reference-gas calibration system consists of the two CO_2-in-air gas mixtures that bracket the ambient concentration and are used hourly to check the stability of the analyzer. It is the results of these hourly checks that are used to scale the hourly averaged value. At weekly intervals a more complete calibration is performed using four additional reference gases with a larger span. This calibration of the working tanks is performed as described by Komhyr et al. (1985). Calibration gases flow for a period of 5 min, which is approximately 20 times the time constant of the analyzer-flow system.

The recalibration of the two CO_2 working tanks, W1 and W2, which are sampled hourly to scale the data, is performed weekly. The calibration consists of using four secondary standard gases labeled LO, MD, HI and Q. The specific concentrations and the tank serial numbers are listed as CO_2 tank constants. (See Table 1.) The gases are sampled in alternate ramps of increasing and decreasing order by concentration. Each ramp, therefore, consists of six "steps" of 5-min duration. From the 5-min period the gas flows through the analyzer, only the voltages from the last 2 min are averaged. (The first 3 min are disregarded.) Two such ramps constitute a cycle. The computed concentrations for W1 and W2 are determined from a least-square regression analysis quadratic fit to the voltages determined from the secondary standard gases (see Table 1). The columns labeled RSF L-M and RSF M-Q are the recorder-scale factor based on two gas pairs computed as follows:

$$\text{RSF L-M} = [(\text{voltage}_M - \text{voltage}_L)/(\text{conc}_M - \text{conc}_L)] \times 10$$

$$\text{RSF M-Q} = [(\text{voltage}_Q - \text{voltage}_M)/(\text{conc}_Q - \text{conc}_M)] \times 10.$$

The scale factors as they are reported in Table 1 are in units of ppm/V × 10. The last column in this table (DELTA) is the difference between the two scale factors. This is a measure of the nonlinearity in the CO_2 analyzer calibration. The printout concludes with a table of the average and standard deviation of the W1 and W2 determinations. These statistics are based on five cycles which yield a standard deviation of less than 0.1 ppm. If this criterion is not satisfied after cycle 5, the cycle with the largest deviation in the concentration of W1 or W2 from the mean is flagged with an asterisk and another cycle is run. Cycle 0 is always deleted because it is required to flush the system. DELTA is the difference between the computed concentration and the assigned value as reported at the top of the page.

The interpretation of the measurement made during any particular hour is dependent on local wind and stability conditions, which are defined by ancillary measurements of wind, temperature, and sometimes condensation nuclei. (See Harris and Nickerson, 1984, for a complete list of the measurement projects at the observatories.) After a minimum amount of signal conditioning, the CAMS that supports these sensors must accept fluctuating voltages that represent the station pressure, air temperature at two heights, dew-point temperature and wind speed. The wind direction is converted to a binary signal where 1 bit equals 1.4°. The signals are processed in much the same fashion that the CO_2 analyzer output is processed, the major exception being the wind record where east–west and north–south components are computed from the original signals. A table containing the sine and cosine values for the specific angles for a single quadrant is used to compute the components. The averaging is performed on the orthogonal component to supply 1-min and hourly averages. The arctangent is determined us-

TABLE 1. A printout of the results of the GMCC report six-point calibration that is conducted weekly. (Top) The assigned CO_2 constants. (Bottom) The derived concentrations for the "working gases."

	CO_2 Tank constants*					
	LO	W1	MD	W2	HI	Q
Concentrations	323.13	335.77	335.82	345.22	348.57	360.62
Serial numbers	461240	472880	472720	459220	472810	538790

	Weekly calibration results				
	Computed concentrations (ppm)		Nonlinearity check (ppm)		
	W1	W2	RSF L-M	RSF M-Q	Delta
Cycle 0[†]	334.47	344.30	2.38	1.28	−1.10
			1.75	1.71	−0.04
Cycle 1	335.73	345.29	1.76	1.68	−0.08
			1.75	1.69	−0.06
Cycle 2	335.72	345.28	1.75	1.69	−0.06
			1.75	1.68	−0.07
Cycle 3	335.70	345.29	1.75	1.69	−0.06
			1.75	1.69	−0.06
Cycle 4	335.68	345.26	1.74	1.69	−0.05
			1.76	1.70	−0.06
Cycle 5	335.64	345.18	1.76	1.67	−0.09
			1.74	1.65	−0.09
Cycle 6[†]	000.00	000.00	0.00	0.00	0.00
			0.00	0.00	0.00
Cycle 7[†]	000.00	000.00	0.00	0.00	0.00
			0.00	0.00	0.00
Average	335.69	345.26			
Std dev	000.04	000.05			
Delta	−000.08	000.04			

* Mauna Loa CO_2, 1985/Day = 101 (0134). Calibration began at Day = 100 (1925).

[†] Cycle not used.

ing a table to obtain the average direction. To obtain a relative measure of the steadiness of the wind direction during the hour, the wind speed is averaged, without regard for coordinates, and the ratio of the resultant wind speed to average wind speed is computed. The display/control panel shows the 1-min average winds, pressure, air temperature, and dew-point temperature.

A printout of the hourly values of those variables that define local meteorological conditions is obtained daily and is used in conjunction with the hourly CO_2 values to evaluate the data quality. The report also provides the station staff a record of conditions. (See Table 2.) Known as the Daily Weather Report (DWR), the listing also serves as a means by which the station staff monitor the quality of the meteorological data. In addition to the listing of the individual values for wind direction (RWD), wind speed (RWS), wind stability factor (SF), station pressure (Pres), air temperature at 2 m height (TempA) and at an elevated height (TempB), dew point (DPT) and precipitation (Rain), a flag is computed hourly. Flags are set if any one variable is missing or out of range for more than 10% of the hour. Flags are also set when the wind is calm for a significant part of the hour, when the dew-point temperature is greater than the air temperature (TempA), and when the cleaning circuit for the dew-point hygrometer is activated. The flags offer a quick reference to the possibility of problems in the system. During a period within 20 min of 0000 GMT, the staff make a weather observation that is reported on the form for comparison with the data taken automatically. The observer is requested to review the data and flags for discontinuities and report all irregularities. The DWR later becomes part of the official station record.

4. Results

It has been possible to realize the design objectives in a microprocessor-controlled system through the use of modular design; the STD BUS, which supports a functional breakdown of the hardware; and the FORTH language, which has constructs that support structured design principles. In a significant way CAMS is a much more integral part of the CO_2 analysis system than was ICDAS. CAMS also satisfies the requirements proposed by Enke (1982) for absorption of computer systems by instrumentation to obtain more reliable operation. With minimal redesign, additional functions can be added to the hardware by adding modules, and

TABLE 2. The BRW, GMCC "Daily Weather Report" for 1 November 1984 that lists the hourly average wind (RWD, RWS), station pressure (Press), air temperature (TempA, TempB), dew-point temperature (DPT) and precipitation (Rain) for the previous 24 hours. SF is the wind steadiness factor; CUT is coordinated universal time.

Day/h (CUT)	Flags	RWD (deg)	RWS (MPH)	SF (%)	Press (in. Hg)	TempA (°C)	TempB (°C)	DPT (°C)	Rain (in.)
306/00	0	118	16	99	29.95	−15.3	−14.8	−17.4	0.00
306/01	0	116	16	99	29.93	−16.1	−15.5	−18.1	0.00
306/02	0	117	17	98	29.92	−15.9	−15.0	−18.1	0.00
306/03	0	114	16	98	29.90	−15.1	−14.5	−17.3	0.00
306/04	0	117	14	99	29.90	−14.3	−13.9	−16.6	0.00
306/05	0	118	14	99	29.89	−14.0	−13.7	−16.5	0.00
306/06	0	118	14	99	29.87	−14.3	−13.7	−16.5	0.00
306/07	0	106	12	97	29.86	−14.0	−13.1	−16.3	0.00
306/08	0	127	10	96	29.85	−13.5	−12.4	−15.7	0.00
306/09	0	114	8	97	29.83	−13.4	−12.7	−15.5	0.00
306/10	0	43	5	85	29.83	−12.9	−12.0	−14.2	0.00
306/11	0	108	5	96	29.82	−13.5	−12.2	−14.5	0.00
306/12	0	85	5	95	29.81	−13.8	−12.5	−14.1	0.00
306/13	0	110	7	97	29.80	−13.6	−12.3	−14.1	0.00
306/14	0	73	6	95	29.80	−13.9	−12.0	−14.5	0.00
306/15	0	62	8	97	29.79	−12.9	−10.7	−13.2	0.00
306/16	0	72	11	98	29.79	−12.5	−10.2	−12.7	0.00
306/17	400	74	11	99	29.79	−12.6	−10.3	−12.5	0.00
306/18	0	70	12	99	29.79	−13.2	−10.7	−13.2	0.00
306/19	0	66	12	97	29.79	−13.6	−11.1	−13.6	0.00
306/20	0	53	14	98	29.80	−12.1	−11.8	−12.3	0.00
306/21	4 000	63	14	97	29.80	−11.1	−11.2	−11.4	0.00
306/22	14 000	56	14	98	29.80	−10.5	−10.5	−10.8	0.00
306/23	0	52	16	98	29.79	−10.3	−10.3	−10.7	0.00

the supporting software can be changed to accommodate such modifications. As it becomes necessary, further control options can be added to the system. Such options may involve the monitoring and control of the flow rate and instrument temperature. In some circumstances it is also advisable to be able to change the sampling source. CAMS could automatically shift the input to the analyzer to a different sampling line if situations dictate.

For the first 3 months of operation, the performance of CAMS has been better than expected. For the most part, the failures have occurred with the cartridge tape drives and the battery-powered RAMs. At the time of installation we found a cartridge tape failure rate of about 1 in 5, which is considerably greater than the failure rate of about 1 in 15 to 1 in 20 of most new equipment. This is attributed to misalignment caused by excessive vibration in transit. In all cases the drives had operated properly in testing before shipment. In the future the drives will be shipped separately and installed or replaced at the observatories.

Of the more than 32 battery-powered RAMs in the system, 2 were found to be faulty. As yet the cause of this failure has not been determined. Analog-to-digital modules have failed at about this same rate. With a complete set of spare boards available at each observatory it was possible to correct the problem in each case and maintain normal operation.

The most significant change in terms of data quality assurance has been the addition of the capability of obtaining listings of the hourly average values from the system or off the resident tape. In this way the station staff can maintain a record of scaled values of carbon dioxide or any of the meteorological values. With respect to the meteorological measurements, an independent observation is made daily at the bottom of the form shown in Table 2. This serves as an independent check on the data. This observation along with a routine scan of the data has provided an excellent guide to data quality. In particular the observers are instructed to annotate any discontinuity in time, unusual flags, or excessive discrepancies between the previous hourly average and the observation. This simple check list has proved very effective at locating questionable data.

REFERENCES

Brodie, L., 1981: *Starting FORTH, An Introduction to the FORTH Language and Operating System for Beginners and Professionals.* Prentice-Hall, 348 pp.

Enke, C. G., 1982: Computers in scientific instrumentation. *Science,* **215,** 785–791.

Harris, J. M., and E. C. Nickerson, 1984: Geophysical Monitoring for Climatic Change No. 12, Summary Rep. 1983. NOAA/ERL Air Resources Lab., 184 pp.

——, J. R. Jordan and G. A. Herbert, 1980: Automation of GMCC CO_2 laboratory operations using microprocessors. WMO No. 549, Special Environ. Rep. No. 14, WMO, 103–108.

Harris, K., 1980: FORTH extensibility or how to write a compiler in 25 words or less. *BYTE,* **5,** 164–184.

Herbert, G. A., J. M. Harris, M. S. Johnson and J. R. Jordan, 1980: Data acquisition and processing in GMCC. WMO No. 549, Special Environ. Rep. No. 14, WMO, 95–102.

Komhyr, W. D., T. B. Harris and L. S. Waterman, 1985: Calibration of nondispersive infrared CO_2 analyzers with CO_2-in-air reference gases. *J. Atmos. Oceanic Technol.* **2,** 1–7.

Mazanec, F. J., Ed., 1984: *The STD BUS Buyers Guide,* **3,** Control Engineering Microcomputer Interface Group, p. 226.

STD Manufacturer's Group, 1985: STD BUS specifications and practice. Rep. No. 106989E, Pro-Log Corp., 2–13.