A Design for Unattended Monitoring of Carbon Dioxide on a Very Tall Tower

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ABSTRACT

Unattended measurements of carbon dioxide (CO_2) mixing ratio at three altitudes up to 496 m above the surface on a television transmitter tower in the southeastern United States have been made for a period of 4 yr. This report describes the design of the automatic tower measuring system in detail. A nondispersive infrared (NDIR) analyzer is used to measure the CO_2 concentration continuously. Real-time control and data collection uses a PC 486 running under the multitasking operating system QNX. The CO_2 data show strong diurnal and seasonal variations, and large vertical gradients. A comparison of this study's 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 36 yr (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 underrepresented (Tans 1991). A project proposed by Tans (1991) is the establishment of an observational network in the continental United States to measure how much CO_2, 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 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 taking continuous measurements of CO_2 on a 610-m-tall television and FM radio (WITN station) transmitter tower 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 multitask operating system QNX (QNX Software Systems, Kanata, Ontario, Canada). Preprocessed 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 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). In addition to CO_2 measurements, the tall tower system began observations of CO, CH_4, N_2O, and a suite of halocompounds at three altitudes of WITN station by automated, in situ gas chromatography (GC) in October 1994. In June 1995 an automated GC was installed at the Wisconsin tower for measurements of CH_4 and CO. The GC design and measurements are discussed elsewhere by Hurst et al. (Hurst et al. 1997).

2. Analysis instrument description

Figure 1 shows a system block diagram for CO_2 measurements on the 610-m 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 height 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 res-

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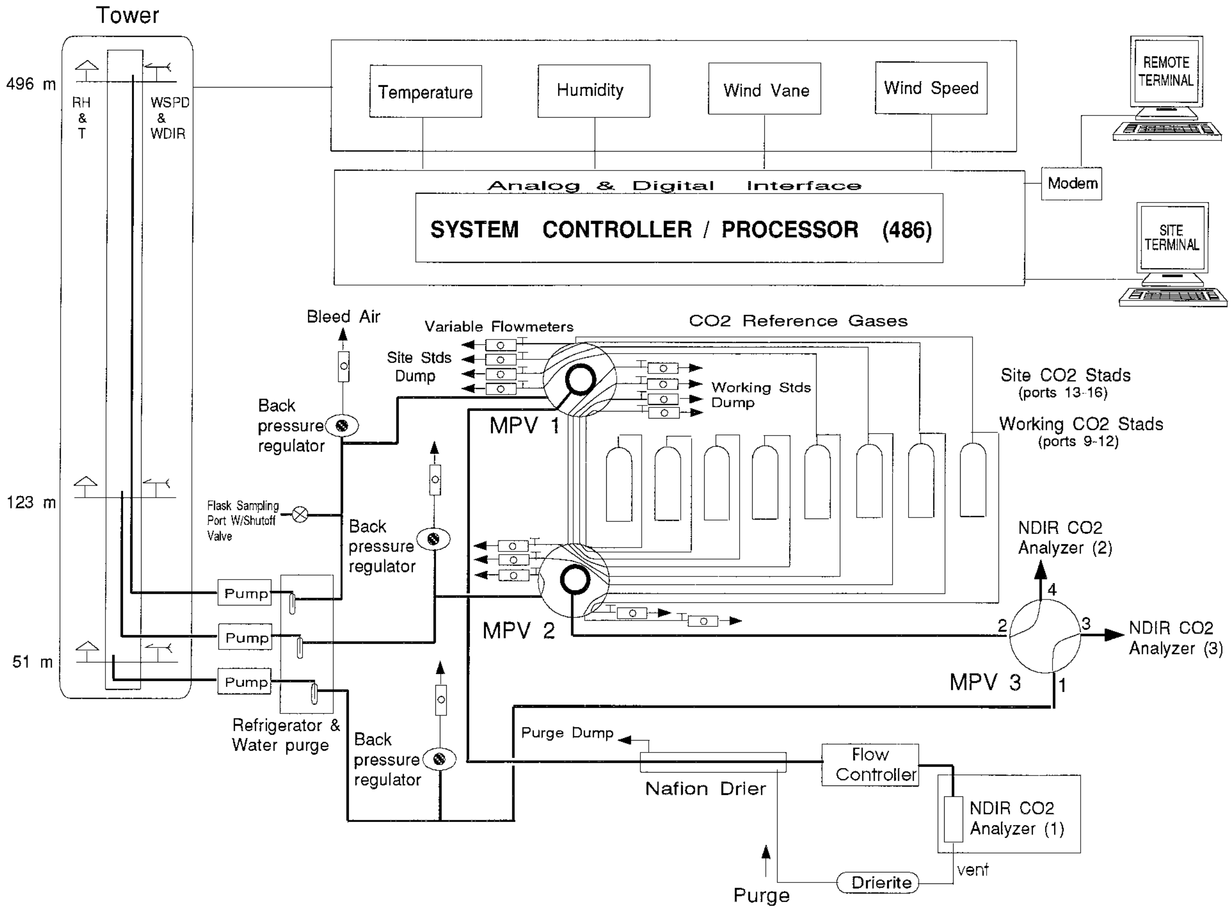

FIG. 1. Instruments and data acquisition and control system for CO_2 measurements on a 610-m TV transmitter tower in eastern North Carolina.

idence 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), which maintains a constant flow through a CO_2 analyzer. Before analysis, this air is further dried to a dewpoint 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 less than 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 (Lincoln, 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 about 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 working 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 h. 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, which are 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 ensure 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 pres-

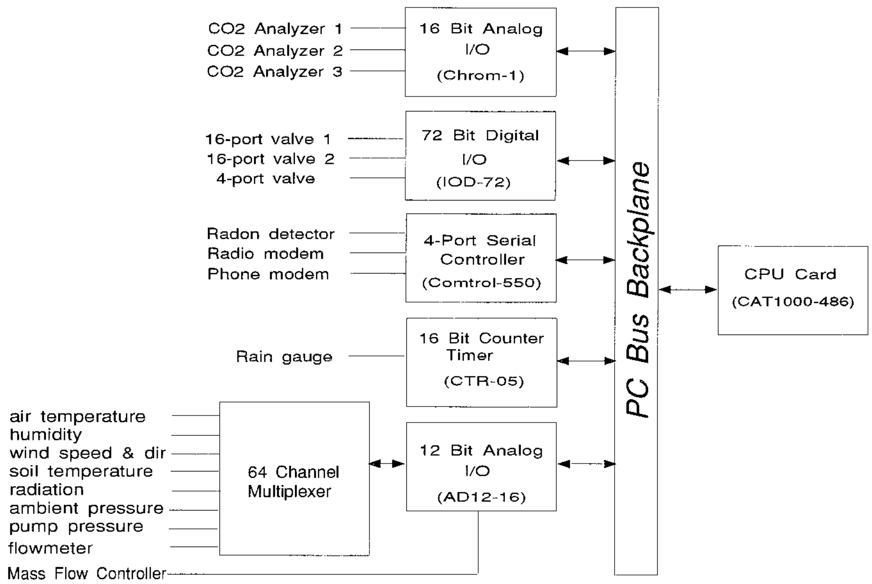

FIG. 2. A block diagram of the data acquisition and control hardware.

sure, as expected. Each Li-Cor is zeroed every 36 min using the 330 ppm standard in order to account for short-term drift in the instrument zero, which 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 measured using an analog barometer (A.I.R., Inc., Boulder, Colorado), incident photosynthetically active radiation (PAR) measured 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, which provide an excellent trace for soil–atmosphere gas exchange and continental air masses. The output of the radon detectors is serial. Paired flasks (2.5 L) are collected weekly from the 496-m level for analysis for CH_4, CO_2, CO, and the stable isotopes of C and O in CO_2, following standard flask analysis 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 onsite 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 Technology, 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.

Analog data from the Li-Cor 6251 CO_2 analyzers 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 signal integration interval is set to 0.5 s. A unique feature is that the board has a +1.0000-V 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 generation of errors through ground loops.

A 12-bit A/D conversion board (ACCES AD12-16, San Diego, California) is used to sample all other analog signals. Configured with the three analog multiplexer boards (ACCES AIM16), the system provides 64 analog input channels. The analog inputs include wind speed, wind direction, air temperature, relative humidity, ambient pressure, pump pressure, soil temperature, room temperature, and radiation. Except pressure transducer outputs (located inside building), all these analog signals are in current loops, which allow 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 V. Having passed through the lightning protection boards, the analog signals from outside sensors are coupled into the analog boards via screw terminal blocks.

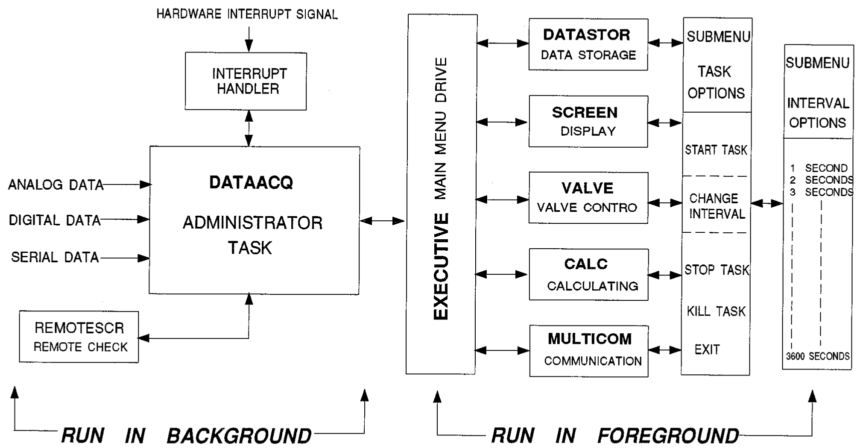

FIG. 3. A block diagram of system software architecture.

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, which may occur due to ice build-up on the tower), the pump will be shut down automatically. In addition, the AD12-16 board provides two-channel analog outputs from digital-to-analog (D/A) conversions, which are used for mass flow control.

Digital output for control of the Valco multiposition valves as well as digital input for status is provided on 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 three multiposition valves. Through the digital board, the computer writes BCD code to switch valves and reads the valve status lines to obtain valve position data.

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. 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 at 2 Hz; counter 1 is used for counting rain gauge tips.

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 s. Port-2 is dedicated to communications via a wireless radio modem (Proxim, Mountain View, California) with a single-board remote computer (OCTAGON 6012, Westminster, Colorado) located on the 496-m tower level; this single board computer collects meteorological data continuously at a 1-Hz sampling rate and transmits data through the radio modem when it receives a data request command from the base 486 computer. 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.

A watchdog timer is used to reset the system if the program stops unexpectedly. The watchdog is enabled or disabled under software control. The time-out is set to 1 s.

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 in the schematic in Fig. 3. All of the software for the tower measurements except the interrupt handler, which is written in 8086 assembler, is written in the C programming language. The real-time operating system QNX permits up to 250 concurrent tasks running per computer. It uses a prioritized (16 levels), time slice scheme with preemptive 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 the computer basic resources such as memory, interrupts, devices, network, etc. Figure 4 shows a simplified flowchart of the DATAACQ program. In an infinite loop, the DATAACQ waits to receive MESSAGES from other client tasks and SIGNALS from the interrupt handler. It reads all

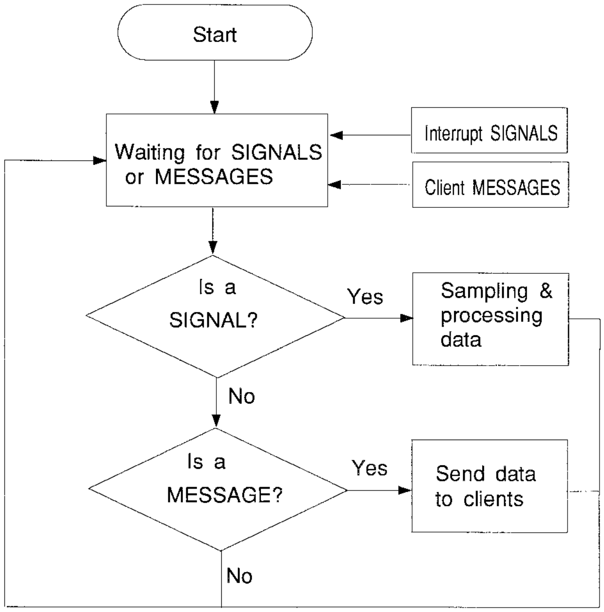

FIG. 4. A simplified flowchart of the administrator task named DATAACQ.

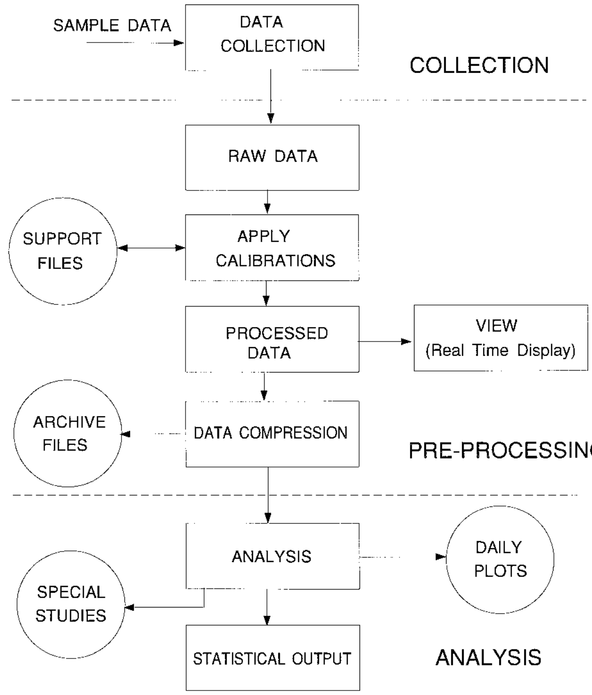

FIG. 5. An overview of data flow scheme.

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 (main menu drive) 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 that are used by the system to set the 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 shut down the data acquisition process.

There is a special task named REMOTESCR that was 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 in to 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 5 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, converting sample counts to raw data in physical units such as CO_2 mixing ratio in μmol mol^{-1}, temperature in degrees Celsius, wind speed in meters per second, etc. Also during preprocessing the calibration information is extracted and used to convert the data to voltages of physical units. A common data compression software package has been developed 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 the sliding window technique (Ziv and Lempel 1977) to achieve compression; 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).

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 and Liu 1976):

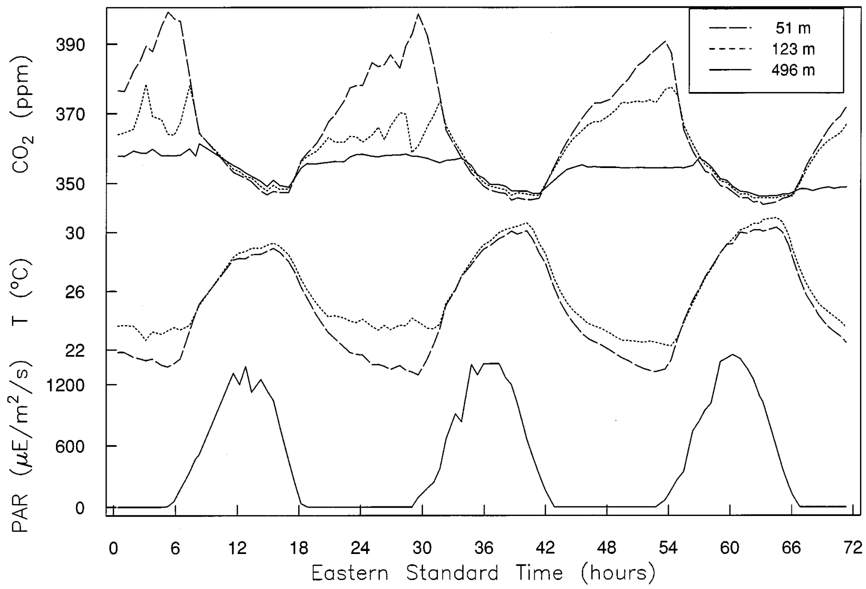

FIG. 6. Three days of CO_2, temperature, and photosynthetically active radiation data in June 1993. Temperature data from the top level were not available because of instrument problems.

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

where x is the output signal and u that of input, $k = T(T + \tau)^{-1}$ is the filter gain, T is the digital sampling period, and τ is the time constant (data average time). To obtain a useful average out of the filter, the sample rate must be faster than the time constant ($\tau/T \gg 1$). The digital filter is essentially a low-pass filter; we can always extend the frequency range of interest by raising the sampling rate. In the tower measurements, the sampling period is $T = 0.5$ s and the time constant equals 30 s, so the digital gain is $k = 0.016$. For more simplicity, (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. First, subtract the current value of the state variable x_{n-1} from the latest input u_n; then multiply the resulting error by k; finally, add the product to the current state. All of these calculations can be performed in one simple line of C code:

$$x = x + k(u - x).$$

Comparing with the moving averaging algorithm, we do not have to maintain any past values of u, only of the current value of x. No function call is required nor is there data structure to maintain. The filter just needs 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 14 June 1992. Valid CO_2 measurements have been obtained for 91% of the period from 14 June 1992 to 31 December 1996. For CO_2, data are most often lost because of problems with the standard gases or failures of the multiposition 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 collected 1.6 Mbyte of uncompressed data per day (approximately 430 kbyte compressed).

Initial results of CO_2 monitoring at the tower have been presented by Bakwin et al. (1995). In Fig. 6 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 the daily average mixing ratios decrease, which is 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, that are 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 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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