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ABSTRACT

A photometer capable of automatically measuring ozone concentration data to very high resolution during scientific research flights in the Earth's atmosphere was developed here at NASA Ames Research Center. This instrument was recently deployed to study the ozone hole over Antarctica.

Ozone is detected by absorbing 253.7-nm radiation from an ultraviolet lamp which shines through the sample of air and impinges on a vacuum phototube. A lower output from the phototube indicates more ozone present in the air sample.

The photometer employs a CMOS Z80 microprocessor with an STD bus system for experiment control, data collection, and storage. Data are collected and stored in nonvolatile memory for experiments lasting up to 8 hours. Data are downloaded to a portable ground-support computer and processed after the aircraft lands.

An independent single-board computer in the STD bus also calculates ozone concentration in real time with less resolution than the CMOS Z80 system, and sends this value to a cockpit meter to aid the pilot in navigation.

Keywords: Ozone Measurement, Automated Ozone Photometer

INTRODUCTION

This photometer was developed to fly on board the NASA ER-2 high-altitude research aircraft for the measurement of ozone concentrations in the Earth's atmosphere for various scientific programs. The new photometer is an improvement over earlier versions in that it consumes less power, has an updated electronic data acquisition and control system, and can measure ozone concentration more accurately and reliably.

A general description of the photometer is presented, followed by a detailed description of the data acquisition, control, and ozone-detection-electronics.

DESCRIPTION OF THE PHOTOMETER

The photometer is enclosed in a rectangular aluminum box measuring 78 × 58 × 25 cm, weighs approximately 20.5 kg, and mounts vertically into the Qbay area of the ER-2 research aircraft (Figure 1). Power, essential aircraft navigation data, and controls are cabled to the instrument. The instrument is insulated on the inside to retain heat, and a temperature controller maintains the inside temperature at about 27°C. A "Standby" switch and an "Ozone On" switch in the aircraft cockpit are the only controls for the instrument while in flight. The Standby switch applies power to the photometer and puts the experiment into a ready mode. When the Ozone On switch is activated, the experiment begins to collect data. Data are collected by the photometer until the Standby switch is turned off (usually after the aircraft has landed) or until the experiment runs out of memory.

The air sample flows into the instrument from a probe mounted on the body of the aircraft that is exposed to the atmosphere. Referring to Figure 2, we see that the air sample first reaches the inlet or isolation valve. This valve is opened by the data acquisition system when the Ozone On switch in the aircraft is turned on (usually while still on the runway prior to the experimental flight) and the aircraft reaches 1500 m. The requirement that the aircraft be at 1500 m before the inlet valve is opened was imposed so that foreign debris from the runway, or other sources, do not get into the air sample measurement path. From the inlet valve the air sample flows to the transfer valve where it is periodically switched between the measurement chamber and an "ozone scrubber" (MnO_2). Once the aircraft is in the air and the inlet valve is open, sample air freely flows throught the inlet valve, through the transfer valve, through the sample chamber, and out an exhaust port.

Levels of ozone are detected with a system employing a Mercury ultraviolet (UV) lamp, a vacuum phototube, and an electrometer circuit which are all mounted on the air-sample-measurement chamber. As mentioned before, the lamp's primary emission is a 253.7-nm radiation. This wavelength is absorbed by ozone so that smaller amounts of radiation are detected by the phototube in an air sample containing ozone. The electrometer circuit output is a frequency proportional to the amount of 253.7-nm radiation detected by the phototube. A second phototube and photometer circuit measures the output of the mercury lamp directly. This is done to compensate for variations in lamp intensity.

The data acquisition and control electronics consists of a CMOS Z80 microprocessor with an STD bus system (1). The experiment timing and control is run by firmware stored in ROM. When the Ozone On switch is activated, the microprocessor begins to run this firmware. During the experiment, air sample UV transmission, temperature, and pressure data are collected and stored into CMOS battery backed RAM. In addition, essential flight navigation data from the aircraft and other housekeeping data from the experiment are also stored. These data are stored in memory in a packed form to save memory space. After the aircraft lands, a portable computer (at present a Kaypro 2000) is attached to the instrument through a serial RS 232 port and the data are downloaded. An independent single board computer (Basicon MC-1i Microcontroller (2)) also plugs into the STD bus to calculate ozone concentration in real time but with less resoltuion than the CMOS Z80 system. The output of this board drives an instrument meter in the aircraft cockpit.

OZONE DETECTION HARDWARE

The ozone detection hardware consists of the UV lamp, the lamp power supply, the two vacuum photodetectors (Figure 2), and the electrometer circuits (Figure 3), all of which are mounted on the air sample chamber.

The UV lamp used is a mercury lamp from BHK Inc. (3) with a dominant emission line of 253.7 nm. The lamp is mounted in one end of the chamber and can be rotated and pushed in and out of its mounting to vary the intensity of the radiation through the chamber.

The lamp is powered by a BHK Inc. power supply whose output is a high-voltage--about 600 V rms--and low current (18 mA rms) 2 kHz square wave to the lamp. The input to the power supply is 15 V dc at about 1 amp. The power supply has the special ability to control the current through the lamp by having the lamp (or load) in a feedback control loop with the power supply. This feedback control is an important feature of the power supply since fluctuations in lamp intensity result in errors in the ozone transmission measurement. The reference detector mounted close to the lamp is used to cancel any errors caused by fluctuations in lamp intensity, but it was found through experimentation and testing that this reference detector and the sample detector do see slightly different geometrical patterns of lamp intensity resulting in unequal proportional changes in detector output for a given perturbation in lamp intensity. For this reason the elimination or at least reduction of lamp intensity fluctuations is very desirable. Although the power supply cannot completely eliminate spontaneous plasma fluctuations in the lamp, it does help to reduce them, as was found through testing. The power supply has a current output drift specification of 0.020 mA/hr (nominal output is 18 mA) and a feedback control time constant of 0.2 sec. A lamp-temperature controller keeps the lamp temperature at about 38°C ±1°C, which is necessary since lamp intensity is a function of lamp temperature.

Two Hammumatsu R765 (4) "solar blind" phototubes are used as the UV detectors--one for measurement and one for reference. These devices were chosen because of their solar blind characteristics: they are not responsive to visible radiation; and these particular devices respond only to a very narrow range of radiation--160 to 320 nm. Since we are interested in only the 253.7-nm line emitted, there is no need for intensive external filtering.

The output of the phototubes is detected by the usual transresistance amplifier circuit shown in Figure 3. Great care was taken in designing and laying this circuit out since it is the front end of the ozone measuring circuitry and any noise generated or amplified here greatly affects the performance of the photometer. The Burr Brown OPA111 amplifier was chosen for its very low noise specifications. The feedback resistors are Caddock TK633 type 1% with a temperature coefficient of 5 ppm or better. Most notably, perhaps, is the time constant in the feedback loop of the OPA111s, which is set for single-pole rolloff of about 3 Hz. This heavy filtering is possible since we are interested only in frequencies of 1 Hz or below from the phototube (the ozone transmission count is integrated for 1 sec). The usual guard rings are used on the front end of the OPA111s to sink any PC-board leakage current which could be seen by the extremely high input impedance of the amplifiers. The AD460L is a high-stability (15 ppm/°C), high-linearity voltage-to-frequency converter used here for its outstanding stability specifications and because we wanted the noise immunity benefits of frequency transmitted information vs voltage transmitted information. Since the AD460L outputs 1 MHz for 10 V into its input, a resolution of 1 ppm in the ozone transmission value output by the phototube represents a 1-Hz output from the 460L or a 10 μV output from the OPA111s.

The DS8830 differential line drivers send the frequency outputs from each of these two channels via shielded twisted pair cables to its own 20-bit binary counter in the STD bus as shown in Figure 4. Each counter consists of two and one-half 74LS590 8-bit binary counters, U1-U6, cascaded into 20 bits. Each counter counts its input frequency for 15/16th of one second. Then the counters are read onto the STD bus, stored into memory, and cleared to zero during the remaining 1/16th of a second. This cycle continues for the duration of the experiment. A Vectron CO236T4Y CMOS crystal oscillator, Y_1 (Fig. 4), running at 32.768 kHz is used as the time base to run the counters as well as the whole experiment. The oscillator is divided down to 16-Hz and 1-Hz stages by the divide by N counters U15 and U17 (Fig. 4). The 16-Hz pulse is used as an interrupt signal to control the experiment timing and the 1-Hz pulse is used as the time base for the 20-bit counters. This oscillator has very tight specifications: accuracy ±1 part per million (ppm), stability ±1 ppm.

With a constant current source of 50 nA into the measurement detector channel, the output was 1 MHz ±2 Hz from the 20-bit counter over the period of 1 hr. Thus, this circuitry is capable of resolving the ozone transmission value down to 4 ppm. Extensive testing and usage of the instrument have shown that the instrument is capable of measuring the ozone concentration to better than 10 parts per billion (ppb) at an altitude of more than 7 km with this circuitry. Typical ozone concentration vs altitude for a flight is shown in Figure 5. The thickness of the line is approximately 10 ppb, which is an indication of the resolution capabilities of the photometer.

EXPERIMENT TIMING AND CONTROL

Timing and control of the experiment is set up in the firmware stored in the 27C64 ROM which resides in the STD bus electronics. When power is applied to the photometer, the Z80 microprocessor runs this firmware. As mentioned before, the experiment is put into a wait loop until the Ozone On switch is activated by the pilot. If the ground support computer is attached to the photometer, the firmware jumps to the ground support routine instead of waiting in the loop for the experiment to begin.

Once the experiment begins, it is divided up into "frames" of time (Figure 6). A frame consists of N_1 seconds or "cells" of "scrubbed" air sample measurements plus N_2 seconds of "unscrubbed" air sample measurements. During N_1, the transfer valve directs the air sample through the ozone scrubber to remove ozone before it enters the air sample chamber. At the end of N_1 seconds, the transfer valve switches and directs the air sample straight to the air sample chamber (the air sample contains ozone). Measurements are not taken for the second following each transfer valve switch to allow the air sample chamber to be purged of old air. This process is repeated for the duration of the experiment. During both the scrub and unscrub phases of each frame, the ozone transmission counts and air sample pressure and temperature are measured once per second, and flight navigation data are measured once every 5 sec. Typically $N_1 = 6$ sec and $N_2 = 54$ sec. Within each cell are 16 interrupts generated by the 16-Hz pulse derived from the crystal oscillator time base. For each of the 16 interrupts there is a task assigned to the microprocessor. At the 8th interrupt of each cell, air sample temperature and pressure are read. Air flight data are read every fifth second. At the 15th interrupt the ozone transmission counters are read. At the first interrupt, the Ozone On switch is read to see if the pilot has changed its position.

During the first cell of each frame of data, a frame header is created for that frame for experiment housekeeping and data reduction purposes. For example, the frame number is incremented, the experiment's real time clock is read, and the ship's clock which is linked to a Geostationary Operation Environmental Satellite (GOES) satellite is read. All of the data from each frame are stored in packed form into the CMOS battery-backed RAM. The photometer continues to run until the power is turned off or the memory is filled. If there is a temporary power failure, the experiment will recommence running after power up, providing that the pilot has left the Ozone On switch on. This power failure is noted by the experiment and stored into a special "log" in memory called the "Experiment Exception Log." This log time-tags and stores experimental events such as power up, isolation valve movement, start of experiment, and memory filled.

CARD CAGE ELECTRONICS AND EXPERIMENT TRANSDUCERS

The data acquisition and control electronics for the experiment consist of an STD bus system and center around a 15-slot STD bus card cage that is mounted in the experiment package. Eight commercial and six custom-built boards are plugged into the card cage. The eight commercial boards include CMOS versions of a Z80 CPU card, five (presently) 64K-battery-backed RAM cards, a dual UART card, and a 12-bit, 16-channel A/D board. The six custom-built boards include the time base for the experiment, two 20-bit counters (for ozone transmission), a real-time clock, input/output (I/O) address decoding circuitry, valve control circuitry, conditioning circuitry, power supplies for the card-cage electronics, and the Basicon MC1i single board computer for the ozone cockpit meter. The power supplies for the card-cage electronics are simple Mil-Spec dc/dc converters. Twenty-eight volts dc from the aircraft is heavily filtered before feeding the +5 and ±15 V dc/dc converters. The heavy use of CMOS components in the electronics results in a very small load (about 1 amp) being drawn from the +28 V by the card cage electronics. With the addition of the lamp power supply and valve loads, the photometer draws a total of about 60 W from the aircraft's 28-V line. The instrument heater draws about 300 W rms from the aircraft's 400-cycle, 115-V line. The transducers in the system include two Rosemount Series 1332 pressure transducers--one fine 0 to 250 Torr and a coarse 0 to 750 Torr--to measure the air sample pressure. Two thermocouple transducers are used to measure the air sample temperature and the ambient temperature inside the instrument package. The temperature transducers include J-type thermocouple wire with Analog Devices 2B50B thermocouple amplifiers. The analog signals from these transducers are processed within the card cage and sent to the 12-bit A/D converter before being read by the microprocessor.

One channel of the CMOS Dual UART Card is used to communicate with the experiment via an IBM-compatible portable computer at 9600 baud. The other channel receives the signal from the aircraft clock at 9600 baud. This clock is used as a common clock to synch all of the experiments on board the aircraft, and as mentioned above can be synched to the GOES time signal.

The Basicon MC1i (2) single board computer includes an Intel-8052 microcontroller chip and contains its own onboard firmware which allows it to run independent of the rest of the system. This board receives only the most significant 16 bits of the 20-bit ozone transmission ratio, the most significant 8 bits of pressure data, and assumes a constant air sample temperature in its calculation of ozone concentration. These approximations simplify the task of calculating ozone concentration, which results in a reduction in resolution to about 50 ppb (from 10 ppb in the CMOS Z80 system). This resolution is quite adequate for an analog meter in the aircraft cockpit with a full-scale defection of 3.5 ppm.

GROUND SUPPORT EQUIPMENT AND DIAGNOSTICS

As mentioned earlier, it is possible to communicate with the photometer via an RS232 line using an IBM-compatible PC. Communication is necessary for three reasons: 1) to download the data from the photometer package after an experiment, 2) to initialize the experiment, and 3) to test the photometer using software diagnostics. A custom ground support software routine was written in PASCAL programming language to allow communication between the computer and the photometer. The same firmware controlling the experiment checks on power-up to see if the ground support computer is connected. Menu-driven software from the computer allows a choice of the above modes to communicate with the photometer. Initializing the experiment clears the memory and sets N_1 and N_2 (the scrub and unscrub periods). Several diagnostic tests that check various portions of the photometer operation can be run from the software. Some of these include reading out the ozone transmission count in real time, reading all temperatures and pressures as well as flight navigation data out in real time, reading and setting the photometer's real-time clock, testing the battery-backed RAM, and reading the photometer power supplies.

SUMMARY

The instrument is capable of measuring ozone concentration in relatively harsh environments to a resolution of better than 10 ppb at typical stratospheric altitudes (7 km). It is compact, light, and consumes relatively little power. The use of battery-backed RAM for nonvolatile storage saves room and increases reliability. The automation of the photometer from the standpoint of downloading data, initialization, and diagnostic testing have proven to be very worthwhile.

ACKNOWLEDGMENTS

The concept of the photometer as well as its scientific aspects was the work of Mr. Walter Starr, the principal investigator for the experiment. The author also wishes to acknowledge the work of Mr. Gregory Bhutz, who wrote the ground support and data reduction software.

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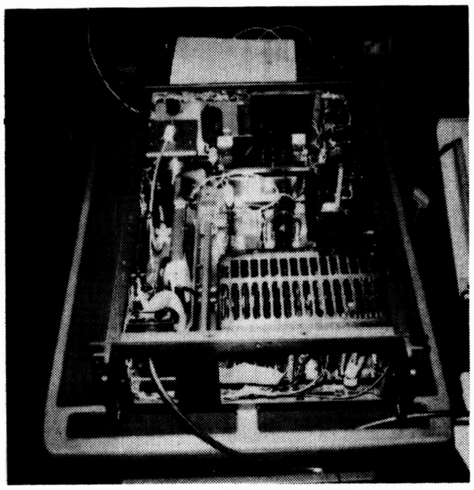

Figure 1 - The Photometer.

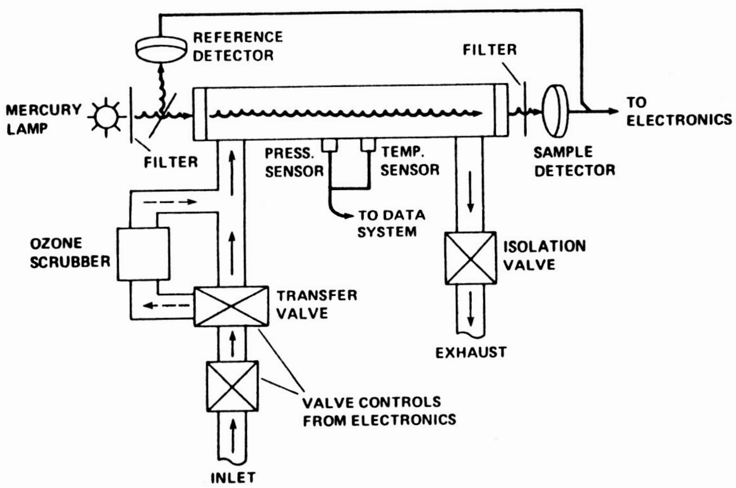

Figure 2 - Ozone Detection Hardware.

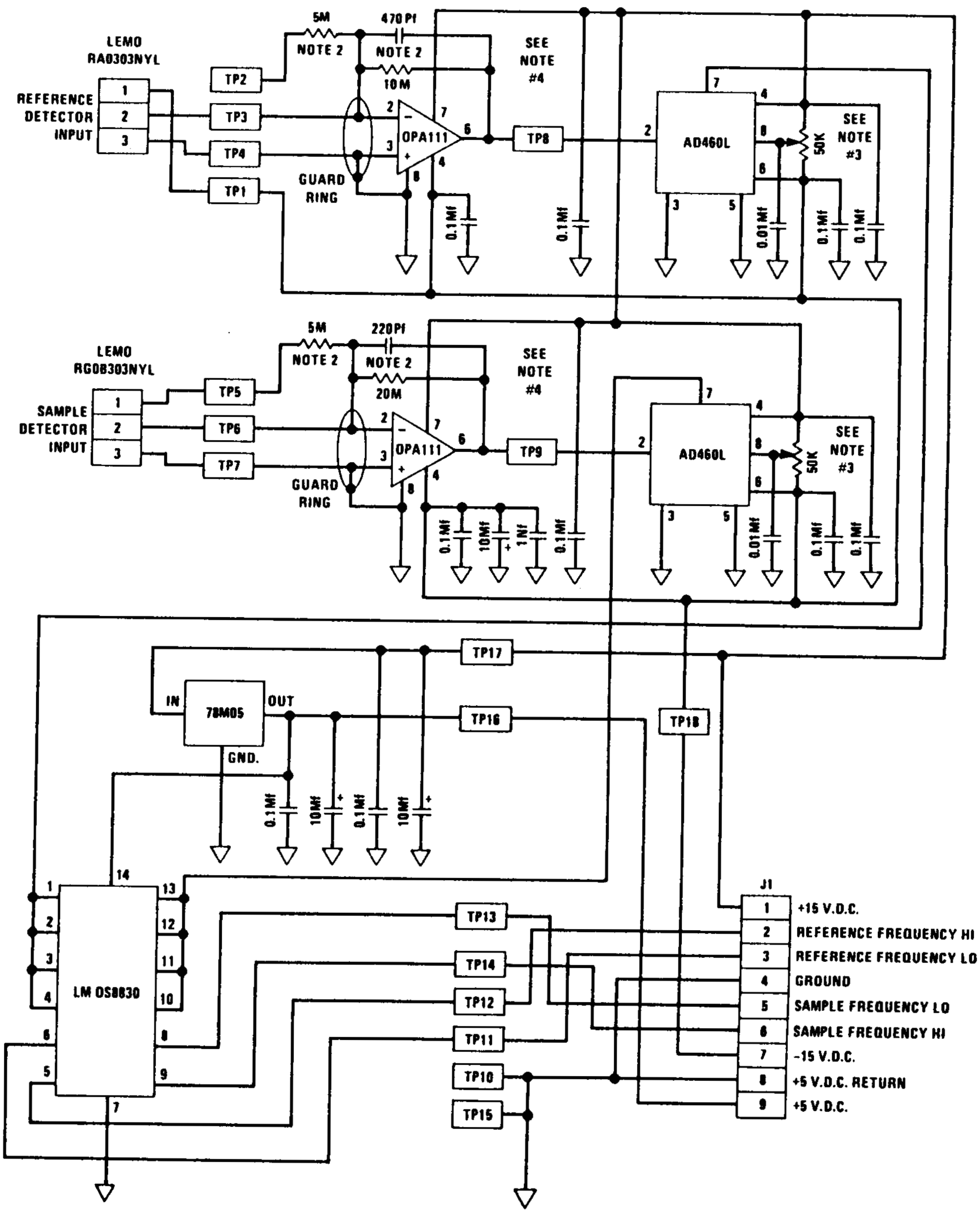

Figure 3 - Electrometer Circuit.

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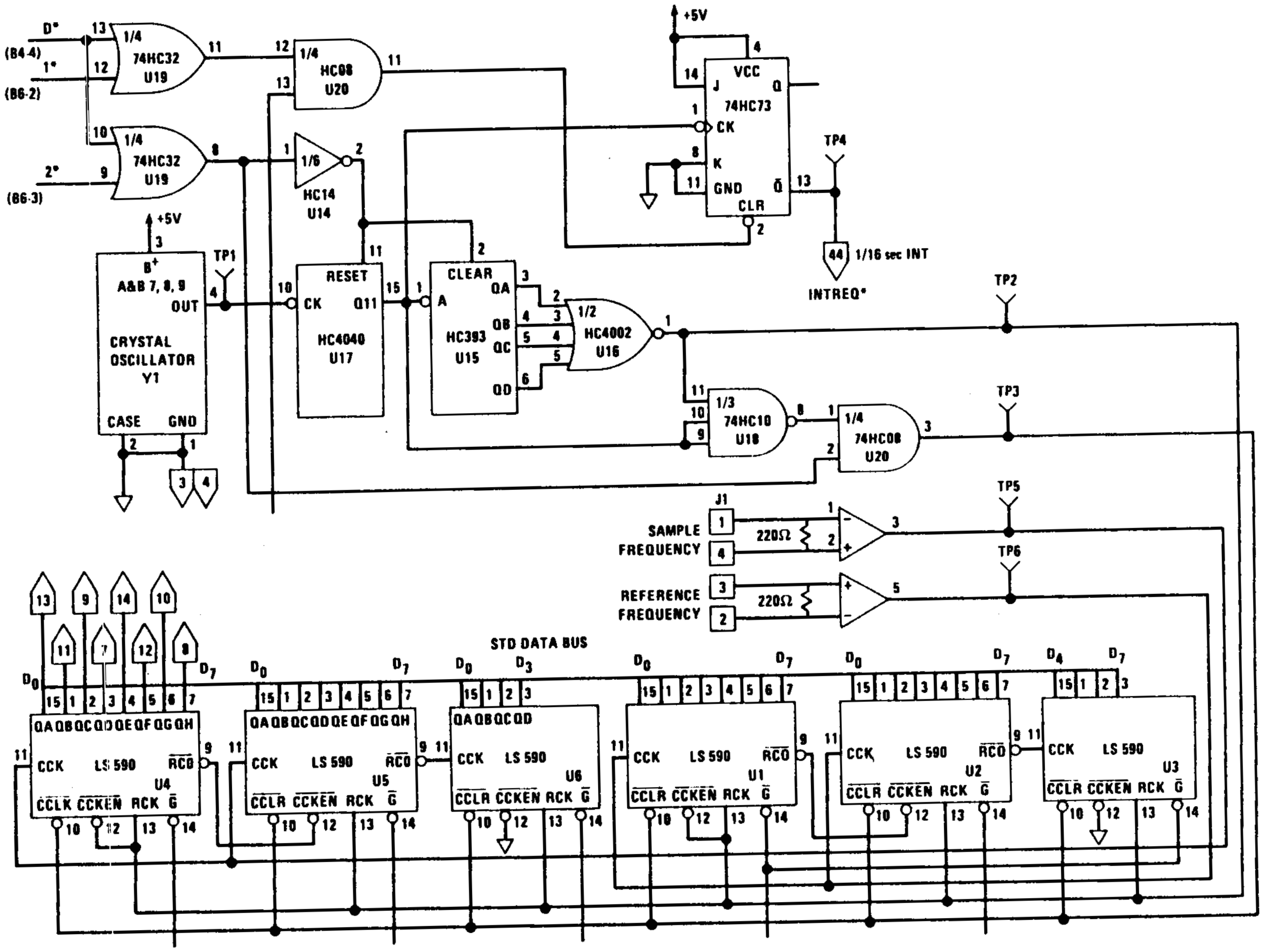

Figure 4 - Ozone Transmission Counters and Experiment Time Base.

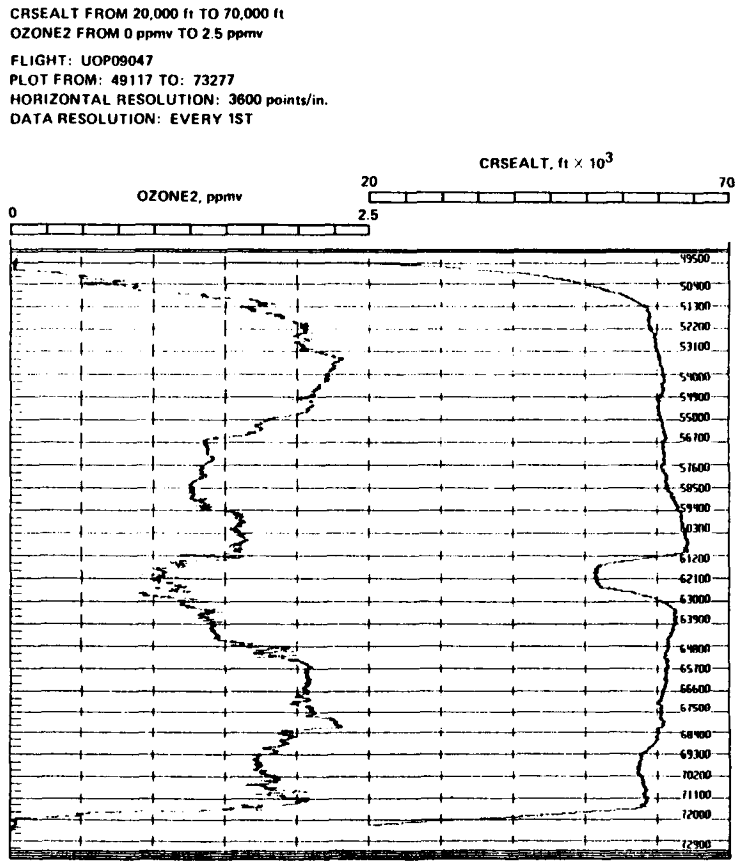

Figure 5 - Data Output From an Experimental Flight.

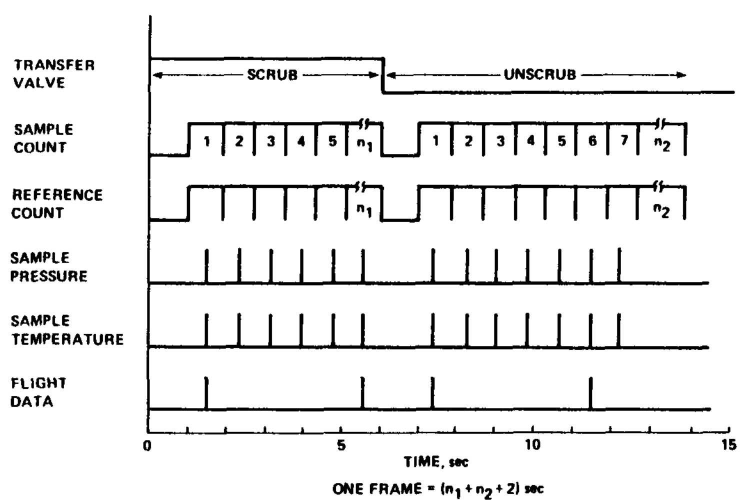

Figure 6 - Experiment Timing and Control.

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16. Abstract

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Ozone is detected by absorbing 253.7-nm radiation from an ultraviolet lamp which shines through the sample of air and impinges on a vacuum phototube. A lower output from the phototube indicates more ozone present in the air sample.

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