

AERODYNE RESEARCH, Inc.

CAPS PM_{ex} Monitor

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*45 Manning Road, Billerica, MA 01821-3976
(978) 663-9500
www.aerodyne.com*

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OVERVIEW

MEASUREMENT SPECIFICATIONS

Measurement Range:	0-4000 Mm^{-1}
Resolution:	0.1 Mm^{-1}
Precision (3σ , 1s):	< 3 Mm^{-1}
Time Response:	< 2 seconds
Baseline Drift:	automated baseline provided
Span Drift:	negligible

PHYSICAL SPECIFICATIONS

Sample Flow Rate:	0.85 liters per minute
Purge Flow:	Provided internally
Cell Pressure:	ambient
Cell Temperature:	~5° above ambient
Power Usage:	< 50 Watts (@120 VAC)
Weight:	12 kg
Size:	~65 cm x 43 cm x 23 cm (L x W x H) [19" rack mount, 5U, 24" deep]

INSTRUMENT CONTROL

1. No external controls on monitor
2. All instrument operating parameters adjustable using software interface using RS-232 connection

DATA OUTPUT

Display	Front Panel, 3 second time constant (± 1 digit)
RS-232	Rear Panel, 1 sample per second or slower (no handshake allowed) DB-9 connector (requires null modem cable, supplied)
USB	For access of on-board stored data (see below)
On-Board	Stored data for subsequent data transfer through USB connection

SAMPLE HANDLING (on back panel)

Inlet	Stainless Steel, 1/4" Swagelok™
Exhaust	Brass, 1/4" Swagelock™

NOTES:

1. The monitor will accept a vacuum up to ~300 Torr below ambient. Low pressure might cause performance degradation caused by mirror contamination. This will occur when the vacuum is released. If a substantial vacuum is encountered, attempt to release that vacuum very slowly to avoid particle upset.
2. For samples with high particle loadings (such as diesel engine exhaust), the user should check the pressure drop that occurs during a baseline measurement period. If the pressure drops by more than 20 Torr, the filter should be replaced.
3. Monitor Battery – The on-board computer that operates the monitor has a black battery case which contains two AA batteries that allows the computer to retain the proper date and time. If this functionality is lost, the two batteries can be readily replaced by simply sliding off the top of the case located on the floor of the monitor enclosure. The data acquisition program will automatically time synchronize the monitor with the acquisition computer at ~ 12 A.M. each day.
4. If extinction levels above 1000 Mm^{-1} are regularly encountered, it is recommended that the sample flow be diluted with particle-free air to avoid both frequent changing of the filter elements and possible mirror contamination.

1. OPERATING PRINCIPLES

The Cavity Attenuated Phase Shift extinction (CAPS PM_{ex}) monitor as deployed here operates as an optical extinction spectrometer, utilizing a visible light-emitting diode (LED) as a light source, a sample cell incorporating two high reflectivity mirrors centered at the wavelength of the LED and a vacuum photodiode detector. Its efficacy is based on the fact that aerosols are broadband scatterers and absorbers of light.

Unlike a conventional absorption spectrometer, in which the concentration of the absorbing species is determined by measuring the attenuation of light, the CAPS monitor relies on measuring the average time spent by the light within the sample cell. The presence of particles causes this average time to decrease as the particle concentration increases because of the propensity of particles to scatter or absorb light. Of course, given the high velocity of light (0.3 m per nanosecond) and the very low concentrations of particles typically found in the ambient environment, a very long path length within the sample cell is required in order to accurately measure this change in time. This is accomplished by forming the ends of the sample cell with high reflectivity mirrors ($R \geq 0.9998$), a configuration which provides an optical path length on the order of 1-2 kilometers. In the absence of particles, the photon lifetime within the cell is on the order of several microseconds, a magnitude which is readily measured with high accuracy.

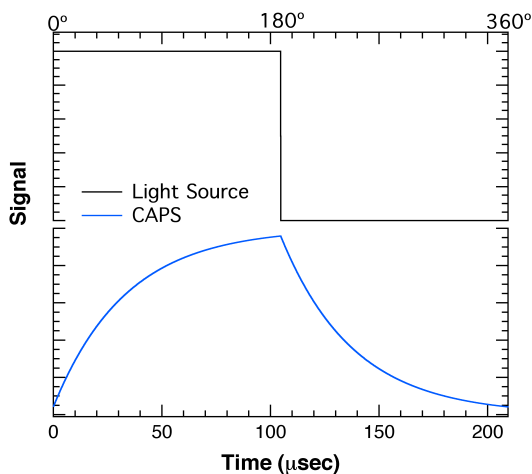


Figure 1. Waveforms of LED (top) and signal at detector (bottom)

In CAPS-based instruments, in order to measure the average time spent by the light within the sample cell, the LED output is square wave modulated and directed into the back of the first reflective mirror. The light beam passes through the absorption cell, out of the back mirror and into a detector where it appears as a distorted waveform which is characterized by a phase shift with respect to the initial modulation. (See Figure 1.) This distortion is the result of an exponential decay of the light within the cell as it leaks out through the mirrors. The amount of that phase shift (ϑ) is a function of fixed instrument properties - cell length, mirror reflectivity, and modulation frequency - and of the presence of aerosols using the following relationship:

$$\cot \vartheta = \cot \vartheta_0 + \frac{c}{2\pi f} \varepsilon$$

where \cot is the cotangent, c is the speed of light, f is the LED modulation frequency, T and P are the sample temperature and pressure respectively, ε is the absolute extinction of light caused by the presence of aerosols. The term $\cot \vartheta_0$ is obtained from a periodic baseline measurement (using particle-free air). Thus,

$$\varepsilon = [\cot \vartheta - \cot \vartheta_0] \cdot (2\pi f / c).$$

Note that this measurement provides an absolute value, requiring no calibration - all the other quantities in the above expression are known. However, it should be noted that this value is averaged over the effective spectral output of the light reaching the detector, a function of the particular LED, bandpass filter and mirror reflectivity.

The configuration of the monitor is quite simple and is shown below in schematic form in Figure 2. The high reflectivity mirrors are directly attached to the ends of the sample cell, forming the optical cavity which provides for the concentration measurement. The LED, optical filter and appropriate focusing optics are attached directly to the sample cell. The light emanating from the cell is directed into a vacuum photodiode where the resultant signal is integrated, digitized and sent to a PC-104 format computer where all subsequent data processing takes place. The sample cell contains both pressure and temperature sensors which allow for both accurate correction because of transient changes in the air Rayleigh scattering. As noted later, the pressure reading is also used to check on the proper operation of the particle filter. The volumetric flow through the cell is limited by a critical orifice that is backed by a diaphragm pump. This same pump is also used to generate a particle-free purge flow that is routed to the mirrors to minimize contamination.

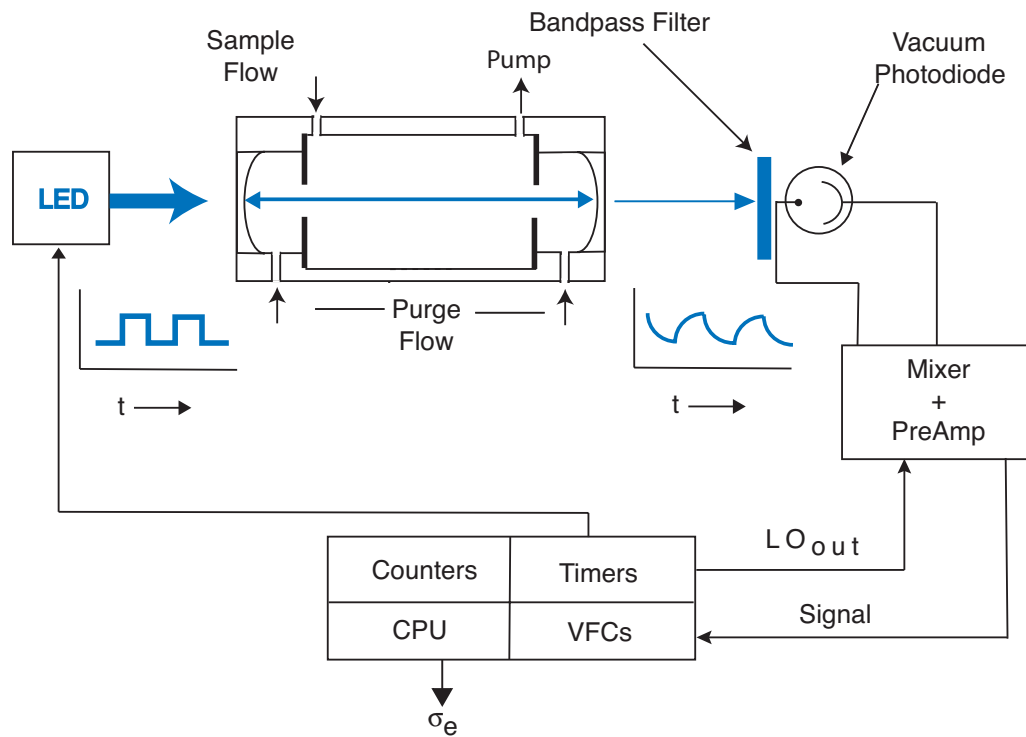


Figure 2 Schematic of CAPS PM_{ex} monitor.

2. GETTING STARTED

1. Unpack shipping crate which contains the monitor, power cord, null-modem data cable with attached serial/USB converter and Netbook computer.
2. Install software on a Windows-based computer if not using supplied Netbook.

REMOVE SWAGELOCK PLUGS ON INLET AND OUTLET PORTS ON BACK PANEL BEFORE POWERING UP.

3. Insert power cord into monitor, plug into wall socket (100-240 VAC) and turn on power switch on back panel. (The fuse for the instrument, which is contained in the power entry module, is a 2A slow-blow fuse.)
4. The supplied Netbook is already configured to operate the data acquisition software. The software will automatically log the data and store it in a folder on the desktop. It also provides all commands necessary to set up the monitor. Connect the supplied null-modem cable to the monitor using the DB-9 port on back panel and to the Netbook computer using the USB/Serial port converter. Start up the software and skip to instruction 5.

If using your own computer, load the data acquisition software on the computer. Connect the supplied null-modem cable to the monitor using the DB-9 port on back panel and to the host computer using either the serial port connector directly or a USB/Serial port converter. Start up the data acquisition software. You will be asked to provide the correct serial port.

5. Within 30 seconds, data from the instrument should start appearing on the display panel. If no data appears,
 - a. Is the cable properly installed and is it a null modem cable?
 - b. Is the serial port properly designated? (Most computers have multiple series and USB ports.)
 - c. Does the com port designated in the monitor software match that being used for the serial port connection?

5. The monitor is now ready for its initial setup. The default mode of the monitor is as follows:

Sample Period:	1 second
On-Board Time Stamp	Igor
Data Delimiter	comma
Autobaseline	Enabled
	15 s flush, 60 s zero periods

The sample period can be set to a number of integer values. It is recommended that sample periods longer than 30 seconds not be used for accurate results. If desired, data can be averaged post-measurement.

There are two different time stamps that can be supplied. The data acquisition software automatically provides a time stamp that mirrors that of the host computer. The monitor can also provide its own internal time stamp that appears in the data file stored on the host data

acquisition computer and also in the data file that is automatically stored on board the monitor. The choice of format for the time-stamp provided on-board is left to the user.

A number of choices for the data delimiter are provided including comma (default), space, and tab.

The monitor is always set to enable automated baseline control upon powering up. This can be disabled using the data acquisition software, but will automatically revert to automatic baseline control once power has been turned off! If this is problematic, the default setting can be changed using the individual software commands listed in Section 6. **We do not recommend this.**

6. Reset the baseline using a manual command if desired.

SHIPPING MONITORS

When units are shipped into the field, run dry air through the monitor for several hours and then plug inlet and outlet ports with Swagelock plugs. This helps to prevent mirror contamination during shipping.

3. AUTOMATED BASELINE

The monitor is provided with an automated baseline capability. Under normal operation, the air/particle sample flows unimpeded into the measurement cell. Upon software command, a valve is powered up which causes the sample flow to proceed through a filter which removes all particles. Upon the end of the baseline measurement, the valve returns to its normal position which bypasses the filter. (see Figure 3)

To use either the automated or manual baseline, the user must provide settings for proper operation of the valve using the supplied software. The two parameters that must be set are flush period and baseline period. The flush period refers to the amount of time required for the sample cell to be completely flushed out of any unfiltered sample; we recommend that this time be set to 10-15 seconds, which is approximately 7-8 cell flush lifetimes. The baseline period is the amount of time required to obtain an accurate baseline reading. We recommend setting this period to 60 seconds – longer baseline periods will not appreciably decrease and might even increase the noise associated with taking a baseline.

If automated baseline operation is required, the user must set the start time for operation and the period between baseline measurements as well. The start time is used to synchronize the baseline measurements with other instruments and can be set to any minute past the hour - the start hour is irrelevant. The period between baseline measurements can be set to any desired length; however, it is

recommended that if the period is less than 1 hour, that it be divisible into 60 (i.e., 10, 12, 15, 20, 30 minutes).

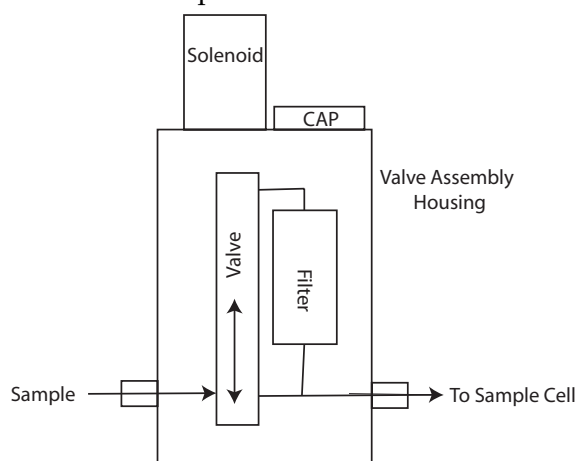


Fig. 3 Schematic of automated filter

The user should be aware that the longer the baseline/flush period and the shorter the interval between baselines the lower the duty factor or actual measurement time. For low particle extinction environments ($<10 \text{ Mm}^{-1}$), it is recommended that if the flush and baseline periods are set to those noted above, the interval between baselines be set to 15 or 30 minutes for best precision. In this case, the duty cycle will be 90% or greater. For higher extinction environments, the interval can be lengthened appreciably.

The instrument as a default condition comes with the automated baseline enabled. This ensures that during ambient monitoring, in the event of a power failure, the instrument continues to operate properly when the instrument powers up upon resumption of electrical service. In laboratory service, the user should consider disabling the automated baseline option using the data acquisition software.

4. DATA OUTPUT

The current extinction reading (with a 3 second time constant) is displayed on the front panel in units of Mm^{-1} (inverse megameters or 10^{-6} m^{-1}). At concentrations below 200 Mm^{-1} , it will provide readings at a tenth of a Mm^{-1} resolution, but will revert to 1 Mm^{-1} resolution at higher concentrations. It will not provide readings above 2000 Mm^{-1} ; however, the digital output will continue to operate properly. The display unit is just a digital voltmeter which converts an analog 0-10 V signal generated by the computer to a digital reading. As such, it is prone to offset errors which limits its accuracy.

The true (and most accurate) readings are provided through the RS-232 connection located on the back panel of the monitor. The data is output as an ASCII file organized in the following order:

Time (chosen format), Extinction (Mm^{-1}), Loss(Mm^{-1}), Pressure(Torr), Temperature(K), Signal(arbitrary units), Flow Sensor($\text{cm}^3 \text{ s}^{-1}$), Status, Last Baseline(Mm^{-1}).

An example of the data stream is show below. This particular example contains a time stamp in hours, minutes and seconds of the day. The data is comma delimited (default setting):

```
101110,131.413,701.26,758.36,302.60,1512.91,xxx,10016,514.09
101111,131.313,701.14,758.27,302.60,1512.91,xxx,10016,514.09
101112,131.326,701.14,758.31,302.60,1512.91,xxx,10016,514.09
```

The example provided above indicates that data was being taken between 10:11:10-10:11:12 A.M, the extinction was $\sim 131 \text{ Mm}^{-1}$, the loss was $\sim 701 \text{ Mm}^{-1}$, and the pressure in the cell was $\sim 758 \text{ Torr}$. The sample temperature was $\sim 303 \text{ K}$, the light signal level was 1513 mV . The next reading is not currently used and is denoted as xxx. The status code (see below) indicates that the monitor pump was on and the system was in its normal monitoring mode and acting as an extinction monitor at an operating wavelength of 630 nm . The last baseline taken was 514 Mm^{-1} (not including the effect of air Rayleigh scattering).

Status is a five digit number: abcde

a) Pump Status

- = 0 Pump Off, Normal Operation
- = 1 Pump On, Normal Operation
- = 2 Alarm

b) Baseline Status

- = 0 Normal Operation – No Baseline
- = 1 Baseline On- Flush Period
- = 2 Baseline On – Measurement Period

c) not used

d) Monitor Type

- = 0 Gas Phase Absorption
- = 2 Aerosol Extinction
- = 3 Single Scattering Albedo Monitor

e) Wavelength

- =4 Blue (445)
- =5 Green (530 nm)
- =6 Red (630 nm)
- =7 Far Red (660 nm)
- =8 Near-IR (780 nm)

The status number is typically used in subsequent data analysis to determine periods of baseline measurement or other upset conditions.

If the supplied monitor software is used to collect the data, a date and time marker which reflects the host computer date and time is automatically attached to the data as the last column, in addition to those listed above.

If the data are being collected with a user-supplied data acquisition program, it is recommended that all these data be recorded. They are required to reconstruct the data if there is a problem with baseline procedures, calibration, etc. and provide highly useful diagnostic information.

On-Board Data Storage

The monitor automatically stores all data on a memory cache located in the computer stack that operates the monitor. It has the capacity to store approximately 6 months of data taken with a 1 second sample period. Once the memory is filled, it will begin to overwrite old data files. Files can be deleted from this memory using the supplied data acquisition program. If the file is to be copied, the USB port on the front panel of the monitor is supplied for this purpose.

Serial Port Parameters:

Baud Rate	9600
Data Bits	8
Parity	None
Stop Bits	1
Flow Control	None

5. MAINTENANCE

Particle Filter Replacement

The only regular maintenance required for the CAPS PM_{ex} monitor is periodic replacement of two filters used in the sample line. The replacement rate depends on the level of particle loading to which the monitor is exposed. Under normal ambient conditions, annual replacement could suffice. However, under high particle loadings (several hundred Mm⁻¹) found when sampling combustion systems, for instance, the period could be a number of hours.

a. Inlet Flow Switching Valve

The first and most important is an in-line filter element which is contained in the stainless steel housing attached to the inlet inside the monitor. This pressure drop across this filter can be measured by using the software command to turn off the pump and “open” the valve; the difference in pressure with and without the pump is essentially due to the presence of the filter. The pressure drop across this filter when new is a few Torr. Once the pressure drop in the filter reaches ~30 Torr, we recommend that the filter element be replaced.

To replace the filter element, unscrew the circular top of the filter enclosure. It is sealed with an o-ring. Pull out the filter element using a pair of tweezers and replace with a new element making sure to properly seat it. Screw the flange back in and snug, taking care not to snag the o-ring on a screw thread. A drop or two of methanol on the o-ring will help. You can buy new elements directly from a supplier.

b. Outlet Filter

A disposable filter (transparent blue plastic) is used to remove all particulates before the sample flows through a critical orifice. This should be replaced periodically, especially when there is a noticeable color change or if the time response of the sensor increases.

Disposable Filter Element: 12-32-60K

Disposable Plastic Filter: DIF-BN60

available from United Filtration Systems (<http://www.unitedfiltration.com>).

equivalent units available from Parker Balston and other suppliers

Mirror Contamination

With proper operation of the monitor, the mirrors should never become substantially contaminated. However, this can occur because of a pressure upset or some other event. However, these monitors can operate within specification even if the mirrors become somewhat dirty. Contaminated mirrors cause a loss of signal and thus decrease in the sensitivity. However, this will not change the span value of the monitor. If the monitor noise increases substantially, one should check the measured optical loss (listed on the display and in the data files). Upon shipping, this value should be between 400 and 550 Mm⁻¹; substantial loss of sensitivity probably would not be noticed until the loss approaches 1000 Mm⁻¹.

The mirrors are readily cleaned. Their coatings are relatively robust and should be treated just as one would treat any multi-layer optical film. Initially, gloves can be employed when handling the mirrors to avoid contamination. However, with practice, these are readily dispensed with.

Required Supplies

1. High quality lens tissue (we recommend ThorLabs)
2. Spectroscopic or HPLC-grade methanol and acetone
3. Clean **glass** bottles with **glass** eyedroppers
4. Supply of particle-free air or Aeroduster
5. A means of holding the 1" mirrors in place while cleaning – a plastic or Teflon block with a shallow wedge or cylinder with appropriate shoulder will work well. [CRD Optics sells inexpensive blocks suitable for this purpose. (<http://www.crd-optics.com/crd-blocks.html>)]

Removal of Cell from Monitor

1. Shut down monitor, remove power cord and take off monitor case cover using supplied Allen wrench (5/64"). Screws are 6-32 (3/8" long).
2. Disconnect the Swagelock fittings (i.e., two 1/4" tees for the sample and one 1/4" tee for the purge flow) attached to the sample cell .
3. Disconnect the wires coming out of the back of the cell from the power block located on the cell mounting block.
4. Unscrew the four (8-32) screws holding the cell in its holder and remove top cover.
5. Carefully slide the cell from the plastic sleeve attaching it to the detector block without rotating detector cylinder.

Removal of Mirrors from Cell

1. Starting at one end, unscrew optics holder, making sure to keep cell upright.
2. Remove o-ring from mirror using tweezers – o-ring might be attached to insides of optics holder. Do not misplace o-ring as it is required for proper operation of monitor.
3. Turn cell upside down and allow mirror to drop out of cell. Some tapping of cell might be required.
4. Repeat at second end to remove second mirror.

Cleaning of Mirrors

1. In a reasonably particle-free environment, place mirror on holding block with curved side of mirror up. The curved side will have a circular mark near the mirror edge.
2. Put the near edge of a single lens paper sheet on the mirror and allow 1-2 drops of solvent to fall on paper. (Do not overwet!! This is a beginner's mistake.)
3. When the mirror becomes fully wetted, draw the lens paper along mirror towards you. Repeat multiple times, first with acetone and then with methanol. With practice, one sheet of lens tissue can be used to make 3 different swipes. We recommend making at least 6 swipes with acetone and 6 with methanol.
4. Use dry air or emission from Aeroduster to remove any excess solvent.

Replacement of Mirrors in Cell

1. Place curved side of mirror into one end of cell, making sure that it is securely seated.
2. Replace o-ring on back surface of mirror.
3. Screw optics holders onto cell. They should be screwed on firmly but not overtightened – the aluminum threads can be damaged.
4. Repeat with other mirror.

Putting the Cell Into the Monitor

1. Slide the cell back into the plastic sleeve on the detector block. Be careful not to rotate the metal cylinder on the detector block.
2. Rotate gas fittings into position and attach Swagelocks – remember to attach the purge flow connection!
3. Put back clamping plate and screw down; it should go metal to metal.
4. Reattach wires to power block taking care to **match the color of the wires** –black to black and red to red.
5. Put back cover with screws.
6. Turn on monitor

Note on mirror cleaning

Learning to clean mirrors takes practice and patience. If you attempt to clean the mirrors and the results are worse than before or if they do not improve, just keep trying. Make sure that there is no lint or other particulate contamination on the mirror surface. A single visible particle is sufficient to cause substantial optical loss. Avoid performing this operation in high relative humidity environments as the evaporation of solvents can cause liquid water condensation on the mirrors.

Cell Maintenance

If the cell itself becomes contaminated, simply clean it in an ultrasonic cleaner with dishwashing detergent or other mild soap or detergent, rinse with water and then with methanol. Allow to dry thoroughly. Do not attempt to clean the inside of the cell with a brush or other device. The surface on which the mirrors rests contains an easily damaged knife-edge which controls the alignment of the mirrors. If damaged, the cell must be replaced.

6. SOFTWARE COMMANDS

The following software commands are provided for those who want to control the monitor using their own software. Commands are entered as ASCII characters over the RS-232 connection. < > denotes a keystroke which is not a simple letter and _ denotes a space. These commands can also be used using the supplied data acquisition software.

General Information

All letter commands begin with <esc> and end with <cr> . (Note that <cr> here means 0x0D; <lf> (0x0A), if present, is ignored.) Some commands take 1 or 2 integer arguments, and where used, they are separated from the command, and from each other, by at least 1 space. While taking data, except for ?, these commands take effect at the conclusion of each observation. Thus, if data is being sampled at 10 seconds, it can take that long for the command to take effect.

Commands active while taking data:

<i>Command</i>	<i>Argument</i>	<i>Function</i>
<esc>		Clear input buffer
<bs>		Delete Last Character
?		Ping; causes immediate return of ! character (0x21) in reply
B/b		Increase (Decrease) Pilot Light (front panel)1 step
F/f		Activate (Deactivate) Valve
P	{_0...4}	Select Front Panel Reading 0=Extinction (Mm^{-1}); 1=Pressure (Torr); 2= Temperature (K); 3 = Signal (mV), 4 = Flow (sccm)
Q		Leave Data Acquisition Mode and enter Interpreter Mode
V/v		Turn on (off) pump
X		Reply with "%DATA"
Z		Start Baseline Measurement Mode
z		Reset Baseline to 0

Commands Active in Interpreter Mode (reached by typing {Esc}Q)

entered as {Esc}command _ Argument1_Argument2 (if required) where _denotes space

<i>Command</i>	<i>Argument</i>	<i>Function</i>
<esc>		same as above
<bs>		" "
?		" "
A	none x_filename	start saving to default file save to filename
B/b		Increases/ diminishes pilot light brightness
C		
D	mm/dd/yyyy	set date
E		Return Setup Table
F/f		Operate valves as in Run Time
G/g		Accept/Reject revised settings, return to measurements
H/h		Enable/disable Automatic Baselines
I		system status (integer divisors, mod and IF, actual integration time)
i		system status (autobaseline info, autosave info.)
J	sourcefilename_destinationfilename	transfers specified file to USB memory device – allows one to change file name for transfer NOTE: DOS terminology sourcefilename C:\Data\Sourcefilename destination file name D:\Destinationfilename IF USB DEVICE NOT PRESENT, SYSTEM WILL REBOOT IN 15 SECONDS
K	sourcefilename	transfers specified file over RS-232 port at enhanced baud rate -when file transfer is completed, baud rate automatically returned to 9600 baud
M	table number_value	modify setting (2 nd Esc return clears this command)
P		provides true zero to panel meter
p	newvalue	sets zero for panel meter

Q/q		Accept/reject settings return to Run Time
R		reboot monitor (same as alt-ctl-del)
S	command string	sends DOS commands to computer (e.g., del, dir) screen information returned
s	command string	sends DOS commands to computer (e.g., del, dir) no information returned
T	hh:mm:ss	Set monitor clock (24 hour time required)
V/v		Turn on/off pump
X		Reply with "%USER"