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MCA-1000 Users Manual

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Summary

The MCA-1000 is a family of low-cost multi-channel analyzer (MCA) for measuring gamma-ray radioactivity with a scintillator.

The PMT-1000 includes a operating voltage supply and plugs directly onto a photomultiplier.

The SiPM-1000 includes the SiPM operating voltage supply and plugs directly onto an SiPM-array.

Using its embedded 32-bit ARM processor, it provides accurate gamma-ray spectroscopy and gain stabilization together with many advanced features such as automatic background subtraction and alarm computations.

This document describes how to use the MCA-1000 from the graphical user interface and from Python scripts. Since all commands are formatted as human readable JSON strings, developers will find they can program the MCA-1000 in any language they want.

Feature summary

- Histograms: Either two 1K×32 or one 2K×32
- More than 60kcps histogramming rate
- Support for positive and negative operating voltage and different PMT pinouts.
- Automatic sample vs background histogramming with alarm function and programmable region of interest.
- Radiation Portal mode with automatic background tracking and programmable alarm
- Only 100mW (5V@20mA) power consumption, USB and serial interface.

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1. Supporting documentation

Open-source software The software is open source and mostly written in Python. Bridgeport Instruments provides a software installer, which by default will create a C:\BPISoftV3 directory. That folder includes Python 3.7 with three added packages: ZMQ (www.zeromq.net), wxPython and Matplotlib v 3.2. ZMQ is used to implement the client-server behavior and it is accessible from more than 40 programming languages. Matplotlib is

used for the graphics interface, and wxPython is used to create a traditional user interface with pull down menus.

The wxMCA folder that contains the MCA software can be placed anywhere on the hard disk. Inside is a folder called documentation and the best starting page is wxMCA/documentation/english/introduction/introduction.html which you can open in any web-browser. This set of linked documents contains a description of every control variable and every data field used by the MCA-1000.

2. Getting started

2.1 Using the USB interface

For USB communication the MCA-1000 uses libusb0.1 (Linux) and libusb_win32 on Windows 10. The Windows 10 libusb dll is digitally signed. When the MCA hardware is present during the installation, the installer will automatically link the MCA-1000 to libusb_win32.

However, it is also possible to simply copy the BPISoftV3 folder onto the C: drive and install the Windows USB-driver manually. This needs to be done only once, and Windows will later recognize any other MCA-1000, by its USB vendor ID of 0x1FA4 and the USB product ID of 0x0101 (PMT-1000) or 0x201 (SiPM-1000).

Open the Windows Device Manager and connect the MCA-1000 to a USB port. Wait until it appears in the Device Manager as an unknown device of type pmtMCA or sipmMCA.

Open the C:\BPISoftV3 folder and launch zadig-2.4.exe. Use Options/List All Devices to refresh the device list and select the device with the BPI vendor ID of 0x1FA4. To the right of the green arrow, select libusb-win32 (v 1.2.6.0) and click the big 'Install Driver' button below. Note that it may take up to 20 seconds for the screen to update - be patient. Once the 'Driver Installation Successful' message appears you can close the window. In the Device Manager you will now see the MCA-1000 listed under 'libusb-win32 devices'.

2.2 Launching the software

First launch the MCA Data Server. Look inside the wxMCA folder. Under Windows, double-click on run_mds.cmd. Under Linux, launch wxMCA/mds/mds_server.pyy making sure you use a python 3.6 or higher installation that also includes ZMQ, wxPython and Matplotlib.

If the MDS reports no MCA found, the OS may have been slow in enumerating the MCA on the USB bus. Kill the MDS and launch it again.

Then launch the User Interface. Under Windows, double-click on run_wxMCA.cmd. Under Linux, launch wxMCA/wxGUI/MCA_Main.py

The items in the menu bar are mostly self-explanatory. You can view results and edit instrument settings in a spread-sheet environment. To send the changed values to the instrument, you need to click on File →to MCA.

3. Energy Spectrum

The MCA provides fast and accurate measurements of energy spectrum and count rates. To acquire an energy histogram, select Display→Histogram from the menu bar. In response, a histogram panel will open. On that panel use "New" to erase the old histogram and count rate data and begin a new acquisition. The panel does not automatically refresh, so click the "Refresh" button to get an updated energy spectrum.

Use "Save" to append the energy histogram and count rate data to a default data data file. The file name is automatically generated and is of the form xyz_histo_status.json where xyz is the detector serial number. By default that file is located in wxMCA/user/mca1k/data. Alternatively, use the Display→Save&nbps;Histogram As to save the histogram where you want it.

3.1 Adjusting operating voltage

You need to adjust the operating voltage to set the maximum measurable energy. In its default setting the MCA has a 1024 bins of which about 900 are being used. Users need to adjust the operating voltage to change the gain of the PMT. In the table below we recommend calibrations for different applications.

662keV peak pos.	*Comment*
662	1.0keV/bin => High gain for measuring low energies down to 20keV
331	2.0keV/bin => Measure NORM up to K-40 at 1460keV
220	3.0keV/bin => Wide range up to Tl-208 at 2615keV

Table 1: Cs-137 calibration for different tasks; NORM: Naturally occurring radioactive materials

Access the operating voltage control by editing cal_ov in the File→arm_ctrl spreadsheet. Enter a new operating voltage in the voltage field and save via File→to MCA.

Go back to the histogram panel and click "New" to start a new acquisition. If you change the operating voltage by 1%, the PMT gain will change by about 6%.

The GUI software can assist with the calibration. To do that it relies on two variable in the auto_cal.json file, which resides in the rad_config/Matplotlib_gui_1k/config folder. the variable cal_energy is the gamma-ray energy you want to use for the calibration. For example, when using a Cs-137 source, cal_energy = 661.62keV. Enter just the energy in keV, without the "keV". Secondly, set the keV/bin variable ("keV_bin") as desired, cf Table1

There is a third variable, related to the type of PMT, but its exact value is not important. By default, pmt_exp = 5.8 which is appropriate for 8-dynode R6231/33 PMT and the 10-dynode CR105. For other 10-dynode PMT's pmt_exp = 7.5 is appropriate. It should be noted that the calibration process will always converge, even if the pmt_exp is not a perfect match for the PMT in use.

To perform the calibration, acquire a spectrum, then adjust fit_min and fit_max such that that they enclose the calibration peak. The algorithm assumes that the calibration peak is the tallest peak in the fit range. The algorithm also selects an appropriately narrow fit range around the peak. It only uses fit_min and fit_max as an indicator of the region where to find the calibration peak.

Acquire a spectrum with sufficient number of counts in the peak, eg 1000 per bin at the peak position. Then click on the "Calib" button. The algorithm will make a fit to the peak, and compare the peak position with where it should be, given the keV_bin and cal_energy variables. From that the algorithm computes a new operating voltage and applies it to the detector. Acquire a new spectrum and observe that now the peak has moved close to its desired position. Repeat these steps until the peak is in the right place.

3.2 Count rate measurement

Observe how the count rate accuracy improves with measurement time. The MCA reports count rates together with their statistical errors. This gives users a useful tool. Manually, or programmatically, they can end a measurement precisely when the desired accuracy has been reached, which saves time and money.

The error (in %) is computed from the number of events as 100*2/sqrt(N), where N is the number of events. This is called the statistical 2-σ error. The true count rate lies within this error range with a 95% probability.

Note that the MCA corrects the recognized count rate using the known dead time per event. Hence the reported count rate is greater than the recognized count rate. The reported count rate is also an accurate estimate of the true number of counts per second. In fact the reported count rate should match the true input count rate with about 1% accuracy (systematic error) for input count rates up to 100kcps. The statistical count rate error is computed correctly using the number of recognized events.

3.3 Dead time

The MCA has a non-extendable dead time of 6.50µs per recognized event.

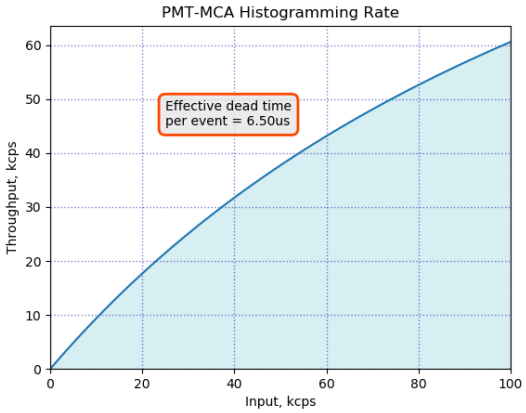


Fig. 1: Expected histogramming rate vs input count rate.

3.4 High count rates

There may be a small gain shift at high count rates. Users should be aware that at input count rates above a few 10kcps there may occur small gain shifts in the energy spectrum. Typically, at 50kcps the gain may fall by about 1%, but the exact gain shift will depend on the PMT that is used on the detector.

4. Sample vs Background

The instrument provides automatic background subtraction. To accurately measure the radioactivity of a weak source, or a weakly contaminated sample can be a complicated process. However, in all cases the process requires a precise measurement of the background and the ability to correctly subtract that background spectrum from the sample spectrum. And the MCA-1000 greatly simplifies this task.

The MCA-1000 stores sample and background data on the instrument and reports the difference. From the dashboard, open the "Sample − Bck" panel. From top to bottom you will see three spectrum displays. The one at the top is the background spectrum. Initially this will be empty. The middle panel has the sample spectrum, and initially it will show the previously acquired spectrum. Finally, the bottom panel has the difference spectrum, which initially equals the middle spectrum.

To acquire a background spectrum, remove all unwanted radioactive materials from near the detector and click on "New" next to the top spectrum panel. You can increase the accuracy of the results by measuring the background spectrum 4 times longer than a typical sample spectrum. Click "Ref" next to the top spectrum to update the display.

Once you have counted the background long enough, click on "New" next to the middle spectrum panel. This starts a new sample spectrum acquisition and stops the background acquisition. The background spectrum will now have stopped and remain unchanged.

If you simply acquire a sample spectrum under the same conditions that you acquired the background spectrum, you will see a similar spectrum grow; click "Ref" next to the middle spectrum to update the display.

Every time the display is updated, the software reads three spectra from the MCA: the background, the sample and the difference spectrum. You will notice, that even the absence of any new radioactivity the difference spectrum is not exactly a flat, empty spectrum. The reason for that is that the gamma-rays arrive randomly and there is therefore a natural statistical variation between acquire spectra.

The instrument computes probabilities and alarms. The MCA computes the probability that the count rate in the difference spectrum was cause by nothing but background. The message box next to the difference spectrum shows the result of that computation. You can confine this computation to a region of interest (ROI) by adjusting roi_low and roi_high in the alarm panel. For instance you can increase the sensitivity to Cs-137 by setting [roi_low, roi_high] to [580, 780]. The ROI is entered as keV and the software converts that into MCA bins using the keV_bin variable from the autocal.json file.

Finally, you can set an alarm threshold. If the probability that the measured sample radioactivity is caused by nothing but background is too low, the MCA can raise an alarm. The alarm threshold can be set in the alarm panel via the alarm_thr variable. For example, a value of 1.0e-3 is interpreted as a probability of 1 in 1000.

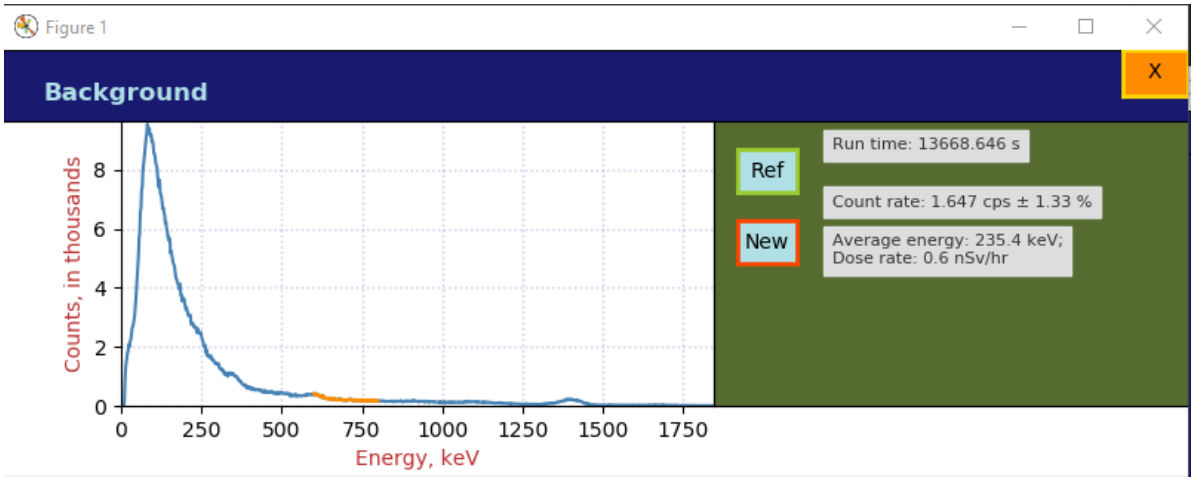


Fig. 2: A background histogram

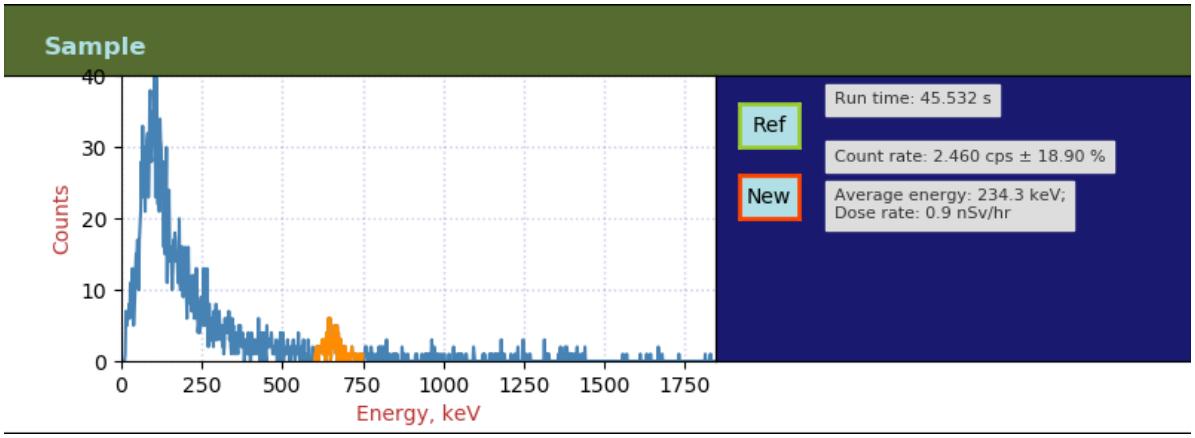


Fig. 3: A sample histogram with a 162kBq (4.4µCi) Cs-137 at 2.5m distance.

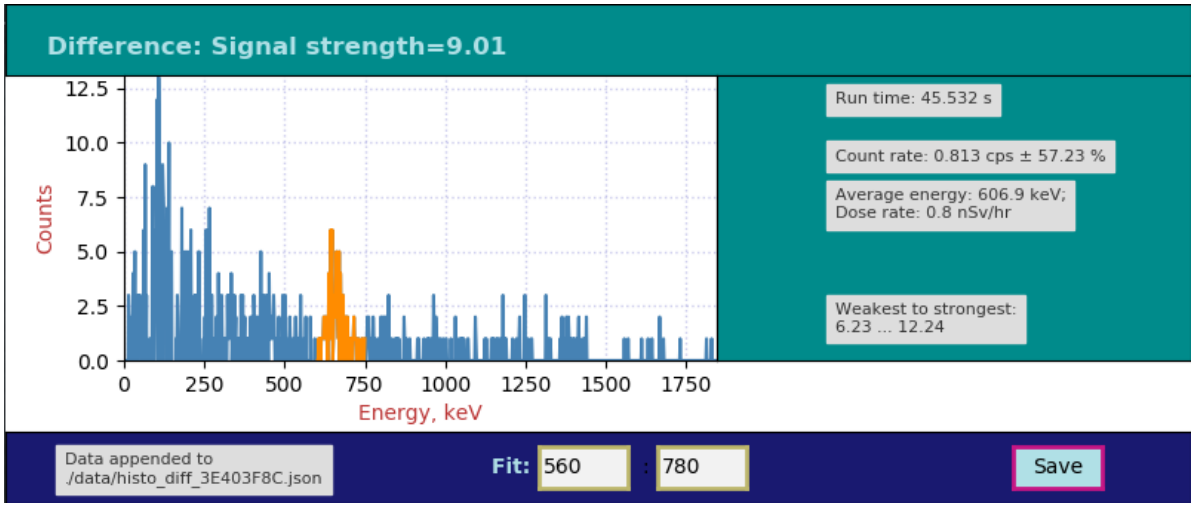


Fig. 4: The back-ground subtracted histogram with an indication of the signal strength. Even though many bins will have negative values, only the positive values are shown for clarity. In this case, the signal was a 162kB (4.4µCi) Cs-137 source at 2.5m distance.

The instrument reports the signal strength and confidence interval. The excess of count rate over background caused by a small amount of radioactivity is called the signal. And like a weak radioactivity signal embedded in noise, the signal strength is what the instrument reports. Here the strength is reported as the negative logarithm of the above-mentioned probability. The instrument also reports the 95% confidence interval for the measured source strength. Users can thus make an informed choice on how to set alarm levels and thresholds for taking a decision. The

mathematics is described in the math box below.

5. Mathematics of Errors and Alarms

This section is for the reader with an interest in the mathematics that is used by the instrument.

5.1 Count rates and their errors

When measuring count rates, the instruments counts events and the elapsed time. Systematic errors for measuring the run time are very small and are ignored here. The dominant variation come from the fact that the number of events during a given time interval is Poisson-distributed. When the total number of events counted is greater than 100, we can approximate the resulting Poisson distribution with Gaussian normal distribution with an average of (μ = number of events) equal to the number of events and a standard deviation of $\sigma = \sqrt{\mu}$ For a given measurement the instrument reports the 2-σ relative count rate error

$$\epsilon = 2/\sqrt{\mu}$$

Dead time does not contribute to statistical error. The instrument knows the incurred dead time per recognized event and computes a live time as run time minus dead time. The reported count rate is events/live_time.

5.2 Background subtraction

Background time can be different from sample time. The instrument can subtract a background spectrum from a sample spectrum even when the two have been acquired for different amounts of time. The calculation for the difference histogram bins is

$$diff = sample - \frac{sample\_time}{back\_time} \cdot back$$

Here, $diff$, $sample$, and $back$ are the histogram bin contents of the three energy spectra.

Count rates are measured by summing all events within the alarm region of interest, and dividing by the respective live times. Count rate errors are computed from the number of events in the region of interest.

The difference count rate is computed as a direct difference, $R_D = R_S - R_B$, from the dead-time corrected sample and background rates.

The count rate error for the difference spectrum has to be computed from the two uncorrelated errors of the sample and the background counting:

$$\epsilon_d = \frac{\sqrt{(R_S \cdot \epsilon_S)^2 + (R_B \cdot \epsilon_B)^2}}{R_S - R_B}$$

Notice that for very small difference count rates the resulting relative error can be quite large. Further, a difference rate with a large relative error, eg 1.0cps ± 200%, simply means that the result is compatible with a difference of 0cps.

5.3 Computing probabilities

For a given sample measurement time, T_S, the MCA knows how many background events to expect on average: $N_B = T_S \cdot R_B$. It compares that number to the number of actually measured events, N_S. Using correct Poisson statistics, not a Gaussian approximation, it calculates the probability that N_S could have been caused by the known background: $P = P(N \geq N_S | N_B)$. If $N_S \gg N_B$, this probability will be very small. If it falls below the given alarm probability (**alarm_thr** in the alarm panel), the MCA can raise an alarm. In other words, a stronger signal causes a lower probability.

However, a user might prefer to use a measure of the signal strength that increases with the signal strength. Hence we define a signal strength as $A = \log_{10}(1/P)$

For the confidence interval of the signal strength, the instrument reports a narrower measure. It computes the two opposites we get by assuming 1-σ errors in the background count and the sample count, but pointing in opposite directions. The resulting rectangular two-dimensional confidence interval contains about 71% of all cases.

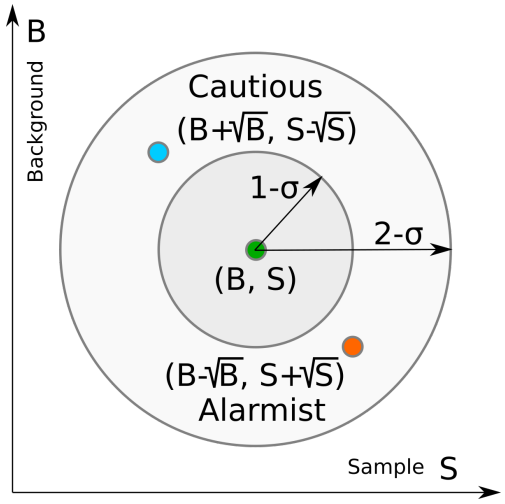


Fig. 5: Two dimensional confidence interval.

6. Radiation Portal Monitor

The MCA can act as a radiation portal monitor with background tracking and a programmable alarm function. In a Radiation Portal Monitor (RPM) the data acquisition unit must perform a number of tasks:

- Continuous background measuring;
- Deliver an alarm within a few seconds after the time of closest approach by a source;
- Keep a few seconds of alarm history so that a polling host will not miss an alarm;
- Automatically reset the system on a continuous alarm to remain operational;
- Support a programmable alarm threshold based on a false-alarm rate;
- Support an adjustable background averaging time, eg 30s for a big gamma-ray detector vs 5 minutes for a neutron detector,
- Be able to recognize passing sources without the aid of an occupancy detector.

The MCA-1000 implements all that functionality within its embedded 32-bit ARM processor. An alarm can be sent as digital pulse with programmable width. The output is fed by a line driver. The chip itself can for a short time source over 3A at 5V – enough to drive a light or a buzzer. Alarms can also be read via USB or the serial communications interface.

The DC output from the line driver must be limited to 30mA. Shorting the line driver output for more than 1ms may render the line driver inoperable. An internal 50Ω resistor provides a series termination to reduce reflections on a 50Ω coaxial cable. With the 50Ω resistor in place the output power is limited to 30mA@3.5V output voltage; ie to 100mW.

6.1 Theory of operation

In the discussion below, times are given in units of time slices. Typically a time slice is 100ms long and the processor perform one RPM computation step every time slice. In some software versions, time slices can be set in multiples of 50ms.

At first the instrument measures the background. On start, after power on or a reset, the ARM processor begins to measure backgrounds. Until backgrounds are know with sufficient precision, the ability to alarm is disabled. This wait time is user programmable, cf **wait** in the RPM panel. Typically the wait time is a fraction of the background averaging time, eg 20% to 50%. A shorter wait time yields an active RPM earlier at an elevated risk for a false alarm until a full background averaging time has passed.

As long as there is no alarm, the events counted during one time slice are considered background events. Using the region of interest **(roi_low, roi_high)** in the RPM panel allows the user to constrain the attention on a part of the energy spectrum.

The background counts per time slice are averaged using geometric averaging. Using the $w = 1/Bck\_avg$ from the alarm panel the processor applies the formula: $B_{n+1} = B_n + w \cdot (N - B_n)$). The background averages are then stored in a 128-long FIFO. This way the instrument can look back 128 time slices to find an untainted background after an alarm has occurred.

We have $0 \leq w \leq 1$ for the weight. If the background at time $t = 0$ changes from B_0 to B_1, The background average responds to a step function with an exponential function of $B(t) = (B_1 - B_0) \cdot (1 - \exp(-t/\tau)$ where $\tau = 1/w$. The standard deviation of the averaged background, ie its noisiness, improves as if $1/w = Bck\_avg$ samples had been averaged.

What happens when a passing source causes an alarm? The instrument continuously computes a moving window sum of the last L

time slices and compares that sum to the number of expected background counts during L time slices. For every time slice the instrument computes the probability that the observed counts could have been caused by the known background, cf the mathematics section above. It computes $P = P(N \geq N_L | N_B)$, with $N_B = L \cdot B$. If that probability is less than **epsilon** on the alarm panel, it will trigger an alarm.

An alarm is typically raised no later than $L/2$ time slices after the closest encounter. For a very strong signal, that alarm may be raised right at the leading edge of the L period; for a weak signal the alarm may be raised about $L/2$ time slices after the source has passed the point of closest approach. In many applications the allowed latency $L/2$ is about 2 seconds, which allows for a 4s summation time. At a time slice length of 100ms this means $L = 40$. In those applications, the time during which the radiation signal is detectable is 4s to 8s and and simulations show that 4s to 6s summation times produce the highest sensitivity; ie lowest minimum detectable activity.

No missed alarms. The instrument keeps a history of the alarm status with a maximum length of 128 time slices. This is controlled by the **history** parameter in the alarm panel. A polling device, via serial interface or USB, will be informed if there was an alarm present in the last **history** time slices. This way a polling host may have a a latency of 128 time slices (12.8s) and still will not miss an alarm.

As long as there is an alarm present in the alarm history FIFO, the instrument will suspend background updates and use the oldest background average in its memory as the best estimator of the background.

Automatic device reset ensures the instrument remains functional when the background suddenly increases. Consider the case of a radiation detection backpack. The wearer walks into a room where radioactive material is present, and this causes an alarm. After **history** time slices, the instrument automatically resets and starts to accept the elevated radiation level as the new background. After a **wait** period (30s typically) the instrument will again be ready to alarm if the operator suddenly encounters an even higher radiation level.

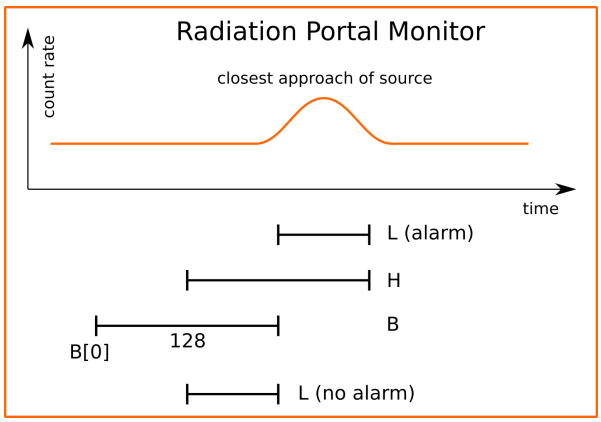


Fig. 6: Programmer's model of the Radiation Portal Monitor software.

7. Analog

7.1 Sample and Hold

The MCA-1000 uses a sample and hold amplifier to measure pulse heights. The input integrating preamplifier has a rise time equal to the light emission time of the scintillator. It is an RC-decay preamplifier without active reset that returns to baseline within 4µs, which sets the minimum theoretical possible dead time between pulses.

7.2 Dead time

The MCA-1000 can operate in 5 distinct modes, each with a different dead time. In all cases, the dead time (T) is non-extendable and the maximum throughput is simply computed as $1/T$.

Mode	*Dead time*	*Description*
0	6.52µs	Standard histogram
1	4.10µs	Counting only
2	13.65µs	Histogram with EMI suppression
3	4.66µs	Arrival times
4	-	Standard histogram with programmable dead time; (reserved)

Table : Dead times in the different operating modes

8. Gain Stabilization

The MCA-1000 provides built-in gain stabilization which can be enhanced with an

LED. In all cases gain stabilization relies on lookup tables to adjust one or more parameters as a function of the measured temperature of the photo-sensor.

The most common approach for both, the PMT-1000 and the SiPM-1000 is to use a single lookup table of the operating voltage vs temperature. That lookup table depends on the photo-sensor as well as the scintillator. It also provides a correct temperature compensation only if electronics, photo-sensor and scintillator are in a thermal steady state. If temperatures are changing too fast and the scintillator and photo-sensor temperature do not have predictable relationship, the gain stabilization cannot perform optimally. In practice it is necessary to thermally insulate scintillator and photo-sensor to make sure they respond slowly and in lockstep to a temperature excursion.

For the PMT-1000 it is also possible to use an LED to assist with the gain stabilization. This is useful if the user wants to compensate for gain drifts of the PMT due to aging and wear-out rather than just temperature. In this case, there will be look up table to predict how the response to the LED light pulse should change over temperature to keep a given gamma-ray peak at the same point in the spectrum; eg a 662keV Cs-137 peak in bin MCA 331 (keV_bin=2.0).

The MCA Data Server documentation shows how the lookup tables are constructed and where they are stored. The included examples show how the lookup tables can be uploaded to the non-volatile memory of the ARM processor.

The MCA-1000 devices ship with a default setting for the lookup tables. All tables are made for NaI(Tl). The voltage vs temperature table is used for gain stabilization mode gs=1; When gs=2, the ARM processor adjusts the operating voltage such that the measured LED response matches the required response at the given temperature.

A gs=1 example: Assume that the detector was calibrated at 25°C, and that now the temperature is 30°C. The voltage vs lookup table may indicate that compared to 25°C the operating voltage at 30°C should be 1% higher. The ARM processor will compute the new voltage target as cal_ov*1.01 and increase the operating voltage accordingly. This will be reflected in the arm_status data in the voltage_target field.

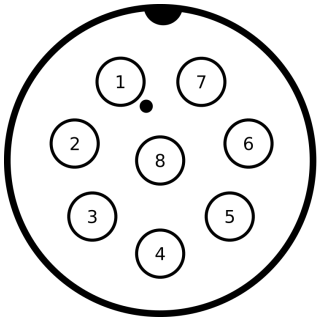
A gs=2 example: A PMT-1000 can be equipped with an optional LED pulser that shines light into the back of the photo-multiplier (PMT). Staying with the above example of calibration at 25°C, the ARM processor looks at the recorded LED value at 25°C. If the temperature is now 30deg;C it will look up by how much the LED value should have changed to maintain the 662keV peak constant. The ARM processor then proceeds to adjust the operating voltage in small and measured steps to ensure that the measured LED response matches the required LED response at 30°C. Note that in this case, the voltage vs temperature lookup table is not used.

9. Mechanical

9.1 8-Pin Connector

The PMT-1000 uses a Bulgin PX0447 mini-B USB connector for power and USB communication. Mating cables are the Bulgin PX0441 (USB-A) and PX0442 (USB mini-A) series cables. They come in lengths from 2m to 4.5m.

The PMT-1000 uses a Switchcraft EN3P8MPX 8-pin connector for GPIO and serial UART communication. The mating connector is part of the EN3C8 series.



PINOUT

1	SWD IO / RX
2	SWD CLK / TX
3	SWD RESET
4	GND
5	VIN
6	TRIGOUT
7	GND
8	GND

Fig. 7: Pinout of the EN3P8 connector.

10. Product and Part Numbers

10.1 Product numbers

The PMT-1000 is part of a product series that all contain an ARM M0+ 32-bit processor for communication and slow control, such as gain stabilization. In the -1000 series the MCA is implemented by software in the ARM processor. In the -3000 series the MCA is implemented independently within an FPGA

for very high-speed operation. The -3000 series also uses a waveform-digitizing ADC and offers detailed pulse capture and real time pulse shape discrimination.

Both types of devices are available for vacuum photomultiplier tubes (PMT) and Si-photomultipliers (SiPM). In both cases, the device generates the operating voltage for the photo-sensor from the incoming 5V.

P/N	*Sensor*	*FPGA*
PMT-1000	PMT	No
SiPM-1000	SiPM	No

Table : Part numbers.

10.2 USB-ID

On the USB bus devices are recognized by their Vendor ID (VID), Product ID (PID) and Serial Number (SN). The vendor ID for Bridgeport Instruments is 0x1FA4. The Product ID's are shown in the table below. Within a product the serial number is fixed, unless BPI makes a custom device that requires a non-standard driver. Note that simple extensions, such as adding a variable to the controls, does not require a new driver.

The BPI software recognizes individual devices by the unique serial number burnt into each ARM processor. The device reports that when the host reads **arm_version**. The serial number communicated in response to USB setup commands is fixed for each part, to avoid that the host keeps adding every new device to an ever longer list of devices requiring a designated USB driver.

P/N	*PID*	*SN*
PMT-1000	0x0101	pmtMCA0001
SiPM-1000	0x0201	sipmMCA0001

Table : Product ID and USB bus serial numbers.

10.3 Device serial numbers

Each ARM processor has an immutable 128-bit unique serial number, which can be printed as a 32-character hexadecimal string. The MCA Data Server always uses the complete 32-character string to identify the device. Because of space constraints, the serial number printed onto the device is shortened to 8 hexadecimal characters.