

SDE Upgrade PLD Firmware Specifications

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Abstract

This document describes the high level specifications for the PLD firmware for the SDE Upgrade Electronics. In particular, it describes the interface between the custom firmware and the embedded ARM processor as well as the necessary interconnections between the various subsections. This document is a work in progress. The most current version is kept in the “docs” subdirectory of the “auger-prime-sde/uub-firmware” github repository.

1 Modules

The development of the PLD firmware is split into several logically distinct, loosely connected, modules to define a high level structure and enable partitioning of the development effort among various institutions.

The major high level modules are

1. Trigger (including event buffers)
2. Time tagging
3. LED controller
4. Digital interface to external detectors

2 Tools

The Xilinx Vivado development tools are used. The highest level which includes the various interfaces the processor via the AXI bus is built using the Vivado block diagram tools. Lower levels of custom firmware are coded directly in Verilog. This structure allows the relatively clean mating to the git repository.

For storage in git a directory structure recommended by Xilinx is used. The shell script “tag_for_git”, located in the base directory scans through a project directory and tag those files that need to be stored in git. Some hand addition or removal of files from git may be required. This helps to avoid temporary files created by Vivado from being stored in git. Please look at the source code for “tag_for_git” to more information about the directory structure it expects. For custom IP in the “ip_repo” directory, the entire tree of the IP should be added to git.

Each WP with firmware has its own master directory in the git repository. For example, front end development work is in “wp1”, the trigger code development work is in “wp2” and time tagging is in “wp3”. Archives of snapshots of the integrated Vivado projects are kept in “wp5/sde_pl_hhddmmyy.tar”, where hhddmmyy corresponds to the ID of the trigger module. In addition to the Vivado project archive, a copy of this file, the sde_trigger header files, and some example programs are included in the tar file.

3 Interconnections

3.1 Modules to Processor

In previous incarnations of the SDE electronics for Auger and Auger North the processor and the PLD firmware were on separate chips. This meant that the PLD interfaced to the processor bus. In fact the PLD looked just like an external static RAM to the processor. This meant that the PLD needed to decode addresses, control signals and strobes.

This is not necessary anymore with the Zynq chip and the Vivado tools. The Xilinx provided bus interface IP can take care of all of those details.

1. The control register interfaces are implemented via a Vivado AXI register peripheral IP.
2. CPU interrupt signals, if required, are implemented via the same IP.
3. Event storage (& associated information) is implemented as double buffered dual ported memory. This will be discussed further in a later section.

3.2 Trigger and Time Tagging Interconnection

In the original Auger (South) design, the trigger and time-tagging circuits are on separate chips. A somewhat elaborate scheme of bus signals was devised to ensure that the correct time-tag was associated with the correct event. This is simplified in the new design.

In order to correctly associate the event time with the event data, the trigger module send a signal to the time tagging circuit telling it to latch the current time. In both previous designs this is simply the number of clock ticks since the last GPS 1PPS signal. But this is not sufficient. The trigger circuit must also tell the time tagging which of the event buffers the time should be associated with. This implies the time tagging and the trigger need to use the same number of buffers. We have chosen to use 4 buffers.

In the original Auger South design we also encode the trigger signal to be able to measure the dead-time of the circuit. That is, the trigger time (actually the end of trace time) is indicated when an active-low signal (called /EVTCLKF in the currently operating design) is asserted. If another buffer is available at that time, the signal returns to its non-active high state after 100 ns. However, if there is no buffer available, the signal remains low until a buffer becomes available. The time-tagging circuit records both edges. In the upgrade dead-time will be indicated by an active high signal “DEAD” from the trigger to the time-tagging modules. The time-tagging module will keep track of the dead-time fraction.

It is important to note that in addition to the shower event data, single muons also recorded for calibration. When a muon calibration buffer becomes full (containing many muons) a muon trigger interrupt is asserted. This requires each of the signals described above to be duplicated for that trigger.

If additional specialized calibration triggers are developed that require their own buffers, then additional copies of the interconnection signals would follow. (For example, we don’t know how to implement an efficient muon decay trigger at present. It is possible this may require something beyond the normal muon buffers.)

The trigger circuit will present to the processor the information detailing which buffer should be read for each event. As long as the processor reads the same buffer from each interface the time tags will remain synchronized with the events.

A corollary to this scheme is that all of the circuits that provide portions of the event data utilize the same “done” signal from the CPU to free up the buffer for a new event. All must use the same trigger signal to close one buffer and move to the next, and that signal should not be set by the processor until the data for an event has been read from all of the interfaces. Presumably the full event readout is done in a single interrupt service routine, so this restriction is not difficult to adhere to.

| Signal | Direction | Description |
|-------------------|----------------------|--|
| DEAD | Trigger→Time-tagging | Active high during time trigger not possible |
| SHWR_TRIGGER | Trigger→Time-tagging | Active high pulse at end of triggered trace |
| SHWR_BUF_NUM[1:0] | Trigger→Time-tagging | Buffer number triggered trace is stored in |
| MUON_TRIGGER | Trigger→Time-tagging | Active high pulse at end of muon buffer |
| MUON_BUF_NUM[1:0] | Trigger→Time-tagging | Buffer number muon data stored in |

3.2.1 Trigger and LED interface

The trigger circuit needs to be informed when the trigger is initiated by a LED pulse. Operationally we wish to be able to initiate a LED pulse of a given amplitude at a given time. The trigger circuit does not need to know anything about the requested amplitude, but it does need to know that there was a LED flash so that it can add a flag to the trigger bits for the event. This is implemented in the sde_trigger module, based upon the VHDL code provided by Roberto Assiro.

3.3 Trigger and Digital Interface

The trigger circuit needs to send a trigger signal to the digital interface circuit. Note that this is not the same signal as that sent to the time tagging circuit. The signal to the digital interface should presumably be prompt,

while that to the time tagging is tied to a fixed bin location within the tank PMT trace. Details are to be defined if/when interfaced detector is specified.

3.4 Interface summary

This section is a placeholder for a summary of the interface signals. At the moment only those between the trigger and time-tagging modules are defined. They are described in section 3.2.

4 Trigger Module

4.1 Register Usage

The register address space of the trigger circuitry occupies 256 control registers and 5 interrupt control registers. Compatibility with the previous register structure has been maintained where practical. Where this is the case the word “Compatibility” will appear in the title, and the register addresses and bit structure will be the same as in the pre-upgrade electronics. Not (yet) implemented features are indicated by cyan text. The symbolic names and addresses of all the registers are defined in the file “sde_trigger_defs.h”, which should be included in any C program that references the registers. (sde_trigger_defs.h is located in the ip_repo/sde_trigger tree.) In addition to register names and addresses, various bit masks and shifts associated with the registers are defined in this header file. Some of the symbolic names and addresses are shown in the included tables. Additional ones can be found in sde_trigger_defs.h. Many of the tables in the following sections include a “Width” field. While all reads and writes transfer a 32 bit word, the “Width” field, if provided, indicates the highest bit of the word read or written that useful. Higher order bits than that return 0 on read, and are ignored on write.

The compatibility mode triggers operate on a signal that has been filtered using a FIR Nyquist filter with a 20 MHz cutoff to approximate the frequency response of the previous electronics. These triggers sample every 3rd bin of the filtered signal. The filtered signals are saved in the shower buffers, in otherwise unused bits, to allow access for debugging purposes. They may be stripped out before sending the data from the local station to the campus. However, the filtered waveform (except for the sampling phase) can be generated by applying a finite impulse response filter to the full bandwidth waveform, as indicated in the code snippet below:

```
int fir[21] = {5,0,12,22,0,-61,-96,0,256,551,681,551,256,0,-96,-61,0,22,12,0,5};
int filt[2048], unfilt[2048];

for (i=21; i<2048; i++)
{
    filt[i] = 0;
    for (j=0; j<21; j++)
        filt[i] = filt[i] + unfilt[i-21+j]*fir[j];
}
```

The code snippet below indicates how to use the bit masks and shifts defined in sde_trigger_defs.h.

```
int wrt_word, rd_word, value1, value2;

// Prepare information to load multi-field register
wrt_word = (value1 & VALUE1_MASK) << VALUE1_SHIFT;

// Extract information from word read from multi-field register
value1 = (rd_word & VALUE1_MASK) >> VALUE1_SHIFT;
value2 = (rd_word & VALUE2_MASK) >> VALUE2_SHIFT;
```

4.2 Compatibility single bin trigger

Compatibility single bin triggers operate on a single ADC time bin, after down-sampling from 120 to 40 MHz. This trigger is controlled by the registers shown below. The new ADCs have 2 more bits, added at the low end,

so the thresholds (above baseline) must be approximately 4 times larger (in ADC counts) than with the previous electronics to replicate the behavior of the original electronics. Note that the signal must be strictly greater than the specified threshold for the trigger to fire. The multiplicity must be greater than or equal to the specified multiplicity.

| Address | R/W | Width | Description |
|---------------------------------|-----|-------|------------------------------|
| COMPATIBILITY_SB_TRIG_THR0_ADDR | R/W | 12 | Threshold for PMT0 |
| COMPATIBILITY_SB_TRIG_THR1_ADDR | R/W | 12 | Threshold for PMT1 |
| COMPATIBILITY_SB_TRIG_THR2_ADDR | R/W | 12 | Threshold for PMT2 |
| COMPATIBILITY_SB_TRIG_ENAB_ADDR | R/W | 10 | Control bits for the trigger |

The bit usage for the COMPATIBILITY_SB_TRIG_ENAB register is as follows:

| Bit(s) | Bit Mask (or << Shift) | Description |
|--------|---|--|
| 3 | COMPATIBILITY_SB_TRIG_INCL_PMT0 | Include PMT0 in multiplicity logic if set |
| 4 | COMPATIBILITY_SB_TRIG_INCL_PMT1 | Include PMT1 in multiplicity logic if set |
| 5 | COMPATIBILITY_SB_TRIG_INCL_PMT2 | Include PMT2 in multiplicity logic if set |
| 7:6 | <<COMPATIBILITY_SB_TRIG_COINC_LVL_SHIFT | Coincidence level for multiplicity logic sub-trigger |
| 9 | | Require 2 consecutive bins above threshold if set |

4.3 Time-over-threshold trigger

The time-over-threshold trigger first applies trigger conditions of the type used for the single bin trigger to individual bins, then counts the number of bins within a sliding window which meet those conditions. If the occupancy exceeds a specified value, a time-over-threshold shower trigger is generated.

A block of 7 registers controls each time-over-threshold trigger instance.

| Name | Address | R/W | Width | Description |
|--------|---------|-----|-------|--|
| THR0 | base+0 | R/W | 10 | Threshold for PMT1 |
| THR1 | base+1 | R/W | 10 | Threshold for PMT2 |
| THR2 | base+2 | R/W | 10 | Threshold for PMT3 |
| | base+3 | R/W | 12 | Not longer used |
| ENABLE | base+4 | R/W | 10 | Control bits for the trigger |
| WID | base+5 | R/W | 7 | Width in bins of sliding window (see below!) |
| OCC | base+6 | R/W | 7 | Occupancy required for trigger |

The bit usage for the ENABLE register is the same as for the single bin trigger above.

The sub-trigger that feeds the time-over-threshold occupancy logic is the logical OR of the enabled multiplicity and pulse height sum sub-triggers.

Note: Previously implemented trigger instances B and C are not present in code versions x260210y and later.

Note: The maximum WID and OCC is reduced to 127 starting with code versions x270711y.

Note: WID is fixed at 120 bins starting with code versions x121211y.

4.4 Time-over-threshold trigger (deconvoluted)

The time-over-threshold-deconvoluted trigger first deconvolutes the typical exponential fall from the FADC trace, secondly applies a pulse height window to each deconvoluted trace, and thirdly counts the number of bins within a sliding window which meet pulse height window conditions. Finally, if the occupancy exceeds a specified value in the required multiplicity of deconvoluted traces, a time-over-threshold-deconvoluted shower trigger is generated. Please note that the order of operations is not the same as for the time-over-threshold trigger above.

Also note that as of version x161012y the signal integral condition in the MOPS trigger registers is also applied to the ToTd trigger, and that the same threshold for the integral applies.

A block of 11 registers controls the time-over-threshold-deconvoluted trigger instance.

| Name | Address | R/W | Width | Description |
|--------|---------|-----|-------|--|
| THR0 | base+0 | R/W | 10 | Lower threshold for PMT1 |
| THR1 | base+1 | R/W | 10 | Lower threshold for PMT2 |
| THR2 | base+2 | R/W | 10 | Lower threshold for PMT3 |
| UP0 | base+3 | R/W | 10 | Upper threshold for PMT1 |
| UP1 | base+4 | R/W | 10 | Upper threshold for PMT2 |
| UP2 | base+5 | R/W | 10 | Upper threshold for PMT3 |
| ENABLE | base+6 | R/W | 8 | Control bits for the trigger |
| WID | base+7 | R/W | 7 | Width in bins of sliding window (see below!) |
| OCC | base+8 | R/W | 7 | Occupancy required for trigger |
| FD | base+9 | R/W | 6 | Decay constant - binary fraction |
| FN | base+a | R/W | 6 | Normalizer - binary fixed point |

Note that the THR_x and OCC conditions are satisfied when the signal is strictly greater than ($>$) the register value, while UP_x condition is satisfied when the signal is less than or equal to (\leq) the register value. Thus writing 1023 to an UP_x register disables that constraint. The bit usage for the ENABLE register is shown below.

| Bit(s) | Description |
|--------|--|
| 0 | Not used |
| 1 | Not used |
| 2 | Not used |
| 3 | Include PMT1 in multiplicity logic if set |
| 4 | Include PMT2 in multiplicity logic if set |
| 5 | Include PMT3 in multiplicity logic if set |
| 7:6 | Coincidence level for multiplicity logic sub-trigger |

FD is obtained from $FD = e^{-\Delta t/\tau}$ where $\Delta t = 25ns$, and τ is the decay time of light in the tank. FD is 6 binary digits constrained to be less than 0.75. The value of FN to load is determined by FD from the equation $FN = 1/(1 - FD)$. It is loaded as a fixed point number xx.yyyy, and must be less than 4. Values of FD and FN are within the allowed range for $\tau \leq 80$ ns.

The following logic can be used to obtain the values of FD and FN to load in the registers.

$$FD = (int) (64. * e^{-\Delta t/\tau} + 0.5)$$

$$FN = (int) (1024./(64. - FD) + 0.5)$$

This trigger is present in code versions x040410y and later.

Note: WID is fixed at 120 bins starting with code versions x121211y.

4.5 Multiplicity of Positive Steps

The multiplicity-of-positive-steps (MOPS) trigger counts positive steps in each FADC trace, accumulating bin to bin steps until the first bin which is smaller than the previous bin is encountered. The aggregate positive step is then subjected to a minimum & maximum height constraint. If it passes this condition the step is added to the count of such steps within a fixed length 120 bin long sliding window. A variable length veto may be applied to ignore aggregate steps following another such step. Finally, if the occupancy exceeds a specified value in the required multiplicity of traces, and the integrated signal exceeds a specified value in those same traces, a multiplicity-of-positive-steps trigger is formed.

The signal integration operates by keeping a running sum of the pulse height in the current ADC time bin minus that in the bin 250 time slots earlier. However, there is a period after a trigger, when no triggers are possible due to finishing the ADC trace or if no buffers are available, in which the earlier time bin is not available in the PLD. While this does not affect any triggered events, it could cause the integrated signal to diverge from zero. In order to mitigate this effect, the integrated signal is exponentially decayed with a time constant of 2048 time bins. The actual integral decays faster than that due to the undershoot following a signal. Note that in any case, the integral

depends upon the history of signals not only in the trace, but before the trace, so an exact offline reconstruction of the trigger is not possible. The integral remains valid for ≈ 250 time bins after the primary trigger. A block of 10 registers controls the multiplicity-of-positive-steps trigger instance.

| Name | Address | R/W | Width | Description |
|--------|---------|-----|-------|--------------------------------|
| MIN0 | base+0 | R/W | 10 | Lower threshold for PMT1 |
| MIN1 | base+1 | R/W | 10 | Lower threshold for PMT2 |
| MIN2 | base+2 | R/W | 10 | Lower threshold for PMT3 |
| MAX0 | base+3 | R/W | 10 | Upper threshold for PMT1 |
| MAX1 | base+4 | R/W | 10 | Upper threshold for PMT2 |
| MAX2 | base+5 | R/W | 10 | Upper threshold for PMT3 |
| ENABLE | base+6 | R/W | 8 | Control bits for the trigger |
| INT | base+7 | R/W | 10 | Minimum integrated signal |
| OCC | base+8 | R/W | 7 | Occupancy required for trigger |
| OFS | base+9 | R/W | 4 | Veto |

Note that the MINx, OCC, and INT conditions are satisfied when the signal is strictly greater than ($>$) the register value, while MAXx condition is satisfied when the signal is less than or equal to (\leq) the register value. Thus writing 1023 to a MAXx register disables that constraint.

The veto is active for $\max(0, \text{int}(\log_2(ph)) + 1 - ofs)$ bins following a aggregate step of size ph . The veto can be disabled by setting OFS to 10 (decimal). Also note that a veto length of 1 has no effect since at least on negative bin to bin step is required to finish an aggregate step. The following table lists some example veto durations.

| OFS | Aggregate step | Veto duration |
|-----|----------------|---------------|
| 0 | 2 | 2 |
| 0 | 3 | 2 |
| 0 | 9 | 4 |
| 1 | 2 | 1 |
| 1 | 5 | 2 |
| 1 | 8 | 3 |
| 2 | 8 | 2 |
| 4 | 8 | 0 |

The bit usage for the ENABLE register is shown below.

| Bit(s) | Description |
|--------|--|
| 0 | Not used |
| 1 | Not used |
| 2 | Not used |
| 3 | Include PMT1 in multiplicity logic if set |
| 4 | Include PMT2 in multiplicity logic if set |
| 5 | Include PMT3 in multiplicity logic if set |
| 7:6 | Coincidence level for multiplicity logic sub-trigger |

This trigger is present in code versions x270711y and later. The minimum integrated signal requirement is present in code versions x081211y and later. Note this uses the register previously used to specify the window length.

Also note that as of version x161012y the minimum integrated signal requirement set for the MOPS trigger is also applied to the ToTd trigger.

4.6 Random Trigger

The random trigger provides a means for the PPC403 to generate a trigger after a specified delay, irrespective of the ADC inputs. It is controlled by a bank of 3 registers.

| Name | Address | R/W | Width | Description |
|---------|---------|-----|-------|---|
| DELAY A | base+0 | R/W | 12 | Low order 12 bits of delay (25ns increments) |
| DELAY B | base+1 | R/W | 12 | High order 12 bits of delay (25ns increments) |
| START | base+2 | W | – | Writing anything to this register starts the random trigger timer |

Only 1 random trigger is generated per write to the START register. Also note that the trigger inhibit will block random triggers with less than 256 clock cycle delay.

4.7 Full bandwidth single bin trigger

The full bandwidth single bin trigger operates on a single bin or small number of consecutive bins. The single bin trigger registers are organized as follows:

| Address | R/W | Width | Description |
|-------------------|-----|-------|------------------------------|
| SB_TRIG_THR0_ADDR | R/W | 12 | Threshold for PMT1 |
| SB_TRIG_THR1_ADDR | R/W | 12 | Threshold for PMT2 |
| SB_TRIG_THR2_ADDR | R/W | 12 | Threshold for PMT3 |
| SB_TRIG_SSD_ADDR | R/W | 12 | Threshold for SSD |
| SB_TRIG_ENAB_ADDR | R/W | 15 | Control bits for the trigger |

The bit usage for the SB_TRIG_ENAB register is as follows:

| Bit(s) | Bit Mask (or Shift) | Description |
|--------|----------------------------------|--|
| 0 | SB_TRIG_INCL_PMT0 | Include PMT0 in multiplicity logic if set |
| 1 | SB_TRIG_INCL_PMT1 | Include PMT1 in multiplicity logic if set |
| 2 | SB_TRIG_INCL_PMT2 | Include PMT2 in multiplicity logic if set |
| 3 | SB_TRIG_INCL_SSD | Include SSD in multiplicity logic if set |
| 6:4 | SB_TRIG_COINC_LVL_MASK (_SHIFT) | Coincidence level for multiplicity logic sub-trigger |
| 8:7 | SB_TRIG_WCD_DELAY_SHIFT | Delay of WCD PMT signals prior to coincidence |
| 10:9 | SB_TRIG_SSD_DELAY_SHIFT | Delay of SSD signals prior to coincidence |
| 12:11 | SB_TRIG_COINC_OVLP_SHIFT | Coincidence overlap width increase (bins) |
| 14:13 | SB_TRIG_CONSEC_BINS_SHIFT | # of consecutive bins required above threshold |

A signal amplitude must be strictly greater than its respective threshold for the trigger to fire. The multiplicity must be greater than or equal to the specified multiplicity. The window for the multiplicity logic coincidence can be set from 1 time bin (8.33 ns) up to 4 time bins. Loading 0 into the SB_TRIG_COINC_OVLP bits sets the overlap to 1 bin, loading 1, sets it to 2 bins, etc. Either the WCD PMT or the SSD signal may be digitally delayed prior to forming a coincidence. Setting the SB_TRIG_WCD_DELAY (or SB_TRIG_SSD_DELAY) bits to 0 adds no delay, setting the bits to 1 adds 1 time bin delay, etc. Additionally, a requirement for more than one consecutive bin for each of the PMT, SSD signals to be above threshold can be added. Setting SB_TRIG_CONSEC_BINS bits to 0 requires just 1 bin to be above threshold, setting it to 1, requires 2 bins to be above threshold, etc.

4.8 Shower memory

This bank of registers controls aspects of the shower memories and provides status information. Currently there are no special compatibility shower memory buffers. The buffers described here are the full bandwidth buffers.

| Address | R/W | Width | Description |
|-------------------------|-----|-------|--|
| SHWR_BUF_TRIG_MASK_ADDR | R/W | 17 | Mask of allowed triggers |
| SHWR_BUF_TRIG_ID_ADDR | R | | Indicates the trigger for the buffer being read |
| SHWR_BUF_CONTROL_ADDR | W | 2 | Resets buffer #N when written |
| SHWR_BUF_STATUS_ADDR | R | | Reports shower memory buffer status |
| SHWR_BUF_START_ADDR | R | | Word offset to start of trace in buffer being read |

The following bits are defined in the SHWR_BUF_TRIG_MASK register. Note that the external trigger is enabled by default after a reset. If SHWR_BUF_TRIG_LED is set in the SHWR_BUF_TRIG_MASK register, then a trigger is generated on a LED flash, even if other trigger conditions are not met. Whether or not this bit is set in the SHWR_BUF_TRIG_MASK register, the presence of a LED flash is indicated in the SHWR_BUF_TRIG_ID register.

| Bit(s) | Bit Mask | Description |
|--------|----------------------------------|---|
| 0 | COMPATIBILITY_SHWR_BUF_TRIG_SB | Compatibility single bin trigger |
| 1 | COMPATIBILITY_SHWR_BUF_TRIG_TOT | Time-over-threshold trigger |
| 2 | COMPATIBILITY_SHWR_BUF_TRIG_TOTD | Time-over-threshold deconvoluted trigger |
| 3 | COMPATIBILITY_SHWR_BUF_TRIG_MOPS | Multiplicity-of-positive-steps trigger |
| 4 | COMPATIBILITY_SHWR_BUF_TRIG_EXT | External trigger |
| 5 | COMPATIBILITY_SHWR_BUF_TRIG_RNDM | Random trigger |
| 6 | | Pre-scale compatibility single bin trigger by 256 if set |
| 7 | | Pre-scale time-over-threshold A trigger if set |
| 8 | | Pre-scale time-over-threshold deconvoluted trigger if set |
| 9 | | Pre-scale MoPS trigger if set |
| 10 | | Pre-scale external trigger by 256 if set |
| 11 | | Pre-scale random trigger if set |
| 16 | SHWR_BUF_TRIG_LED | Trigger on LED flash |
| 17 | SB_TRIG | Full bandwidth single bin trigger |

The following bits are defined in the SHWR_BUF_TRIG_ID register. The initial trigger bits indicate which trigger generated the T1 trigger from the logic. The additional trigger bits flag any trigger conditions that are satisfied by the FADC traces after an initial trigger.

| Bit(s) | Bit Mask | Description |
|--------|---------------------------------------|---|
| 0 | COMPATIBILITY_SHWR_BUF_TRIG_SB | Initial single bin trigger |
| 1 | COMPATIBILITY_SHWR_BUF_TRIG_TOT | Initial time-over-threshold A trigger |
| 2 | COMPATIBILITY_SHWR_BUF_TRIG_TOTD | Initial time-over-threshold deconvoluted trigger |
| 3 | COMPATIBILITY_SHWR_BUF_TRIG_MOPS | Multiplicity-of-positive-steps trigger |
| 4 | COMPATIBILITY_SHWR_BUF_TRIG_EXT | Initial external trigger |
| 5 | COMPATIBILITY_SHWR_BUF_TRIG_RNDM | Initial random trigger |
| 8 | COMPATIBILITY_SHWR_BUF_TRIG_SB_DLYD | Additional single bin trigger |
| 9 | COMPATIBILITY_SHWR_BUF_TRIG_TOT_DLYD | Additional time-over-threshold A trigger |
| 10 | COMPATIBILITY_SHWR_BUF_TRIG_TOTD_DLYD | Additional time-over-threshold deconvoluted trigger |
| 11 | COMPATIBILITY_SHWR_BUF_TRIG_MOPS_DLYD | Additional multiplicity-of-positive-steps trigger |
| 12 | COMPATIBILITY_SHWR_BUF_TRIG_EXT_DLYD | Additional external trigger |
| 13 | COMPATIBILITY_SHWR_BUF_TRIG_RNDM_DLYD | Additional random trigger |
| 16 | SHWR_BUF_TRIG_LED | LED flasher fired |
| 24 | SHWR_BUF_TRIG_LED_DLYD | LED flasher fired after trigger |
| 25 | SB_TRIG_DLYD | Additional single bin trigger |

The following bits are defined in the SHWR_BUF_CONTROL register.

| Bit(s) | Description |
|--------|--|
| 1-0 | Reset buffer full status of specified buffer |

The following bits are defined in the SHWR_BUF_STATUS register.

| Bit(s) | Bit Mask (or Shift) | Description |
|--------|------------------------------|--|
| 1:0 | SHWR_BUF_RNUM_MASK (_SHIFT) | Number of the shower buffer to be read |
| 3:2 | SHWR_BUF_WNUM_MASK (_SHIFT) | Number of buffer currently being written |
| 7:4 | SHWR_BUF_FULL_MASK (_SHIFT) | Bit map of full buffers |
| 8 | SHWR_INTR_PEND_MASK (_SHIFT) | Interrupt pending if set |
| 10:9 | SHWR_BUF_NFULL_MASK (_SHIFT) | Number of full buffers |

4.9 Trigger Rates

The trigger rates block counts reports the rates of several of the triggers accumulated over the last 26.8 seconds. The rate counters are double buffered, so there is always a static value representing the number of triggers during a 26.8 second interval that ended some time between 0 and 26.8 seconds ago. The trigger rate registers are organized as follows:

| Name | Address | R/W | Width | Description |
|---------------|---------|-----|-------|--|
| TRIGGER RATES | base+0 | R | 32 | Rates for single bin, ToT, ToTd, and MoPS triggers |
| DELAYED RATES | base+1 | R | 32 | Rates for single bin, ToT, ToTd, and MoPS delayed triggers |

The information is packed in each of these two registers as follows:

| Bit(s) | Description |
|--------|---|
| 7:0 | # single bin triggers in last 26.8 seconds / 32 |
| 15:8 | # ToT triggers in last 26.8 seconds |
| 23:16 | # ToTd triggers in last 26.8 seconds |
| 31:24 | # MoPS triggers in last 26.8 seconds |

The counts in each field are limited to a maximum value of 252 (fc_{16}). Any rate higher than 252 per 26.8 second interval will read as 252. For example, any ToTd rate higher than about 9.38 Hz will read 252.

4.10 Muon triggers

Multiple muon triggers are implemented to allow various combinations of triggers for WCD & SSD calibration. The muon trigger registers are organized as follows:

| Address | R/W | Width | Description |
|-----------------------------------|-----|-------|------------------------------|
| MUON_TRIG _x _THR0_ADDR | R/W | 12 | Threshold for PMT1 |
| MUON_TRIG _x _THR1_ADDR | R/W | 12 | Threshold for PMT2 |
| MUON_TRIG _x _THR2_ADDR | R/W | 12 | Threshold for PMT3 |
| MUON_TRIG _x _SSD_ADDR | R/W | 12 | Threshold for SSD |
| MUON_TRIG _x _ENAB_ADDR | R/W | 15 | Control bits for the trigger |

The bit usage for the MUON_TRIG_x_ENAB register is as follows:

| Bit(s) | Bit Mask (or Shift) | Description |
|--------|-----------------------------------|--|
| 0 | MUON_TRIG_INCL_PMT0 | Include PMT0 in multiplicity logic if set |
| 1 | MUON_TRIG_INCL_PMT1 | Include PMT1 in multiplicity logic if set |
| 2 | MUON_TRIG_INCL_PMT2 | Include PMT2 in multiplicity logic if set |
| 3 | MUON_TRIG_INCL_SSD | Include SSD in multiplicity logic if set |
| 6:4 | MUON_TRIG_COINC_LVL_MASK (SHIFT) | Coincidence level for multiplicity logic sub-trigger |
| 8:7 | MUON_TRIG_WCD_DELAY_SHIFT | Delay of WCD PMT signals prior to coincidence |
| 10:9 | MUON_TRIG_SSD_DELAY_SHIFT | Delay of SSD signals prior to coincidence |
| 12:11 | MUON_TRIG_COINC_OVLP_SHIFT | Coincidence overlap width increase (bins) |
| 14:13 | MUON_TRIG_CONSEC_BINS_SHIFT | # of consecutive bins required above threshold |

Here “x” is either 1, 2, 3, or 4, corresponding to which of the 4 simple triggers is desired. A signal amplitude must be strictly greater than its respective threshold for the trigger to fire. The multiplicity must be greater than or equal to the specified multiplicity. The window for the multiplicity logic coincidence can be set from 1 time bin (8.33 ns) up to 4 time bins. Loading 0 into the MUON_TRIG_COINC_OVLP bits sets the overlap to 1 bin, loading 1, sets it to 2 bins, etc. Either the WCD PMT or the SSD signal may be digitally delayed prior to forming a coincidence. Setting the MUON_TRIG_WCD_DELAY (or MUON_TRIG_SSD_DELAY) bits to 0 adds no delay, setting the bits to 1 adds 1 time bin delay, etc. Additionally, a requirement for more than one consecutive bin for each of the PMT, SSD signals to be above threshold can be added. Setting MUON_TRIG_CONSEC_BINS bits to 0 requires just 1 bin to be above threshold, setting it to 1, requires 2 bins to be above threshold, etc.

4.11 Muon memory buffers

This bank of registers controls aspects of the muon memory buffers and provides status information.

| Address | R/W | Width | Description |
|--------------------------|-----|-------|---|
| MUON_BUF_TIME_TAG_A_ADDR | R | 30 | Time tag at the beginning of the buffer |
| MUON_BUF_TIME_TAG_B_ADDR | R | 30 | Time tag at the end of the buffer |
| MUON_BUF_TRIG_MASK_ADDR | R/W | 1 | Enable mask of allowed triggers |
| MUON_BUF_CONTROL_ADDR | W | 2 | Resets buffer #N when written |
| MUON_BUF_STATUS_ADDR | R | 11 | Reports muon memory buffer status |
| MUON_BUF_WORD_COUNT_ADDR | R | 13 | Reports number of words in buffer |

The following bits are defined in the MUON_BUF_TRIG_MASK register. This register is at present not really necessary, but is kept to allow the flexibility to add other muon triggers at a later time.

| Bit | Bit Mask (or Shift) | Description |
|-----|---------------------|---|
| 0 | MUON_BUF_TRIG_SB1 | Enable muon simple threshold 1 trigger if set |
| 1 | MUON_BUF_TRIG_SB2 | Enable muon simple threshold 2 trigger if set |
| 2 | MUON_BUF_TRIG_SB3 | Enable muon simple threshold 3 trigger if set |
| 3 | MUON_BUF_TRIG_SB4 | Enable muon simple threshold 4 trigger if set |
| 4 | MUON_BUF_TRIG_EXT | Enable muon external trigger if set |

The following bits are defined in the CONTROL register.

| Bit(s) | Description |
|--------|--|
| 1:0 | Reset buffer full status of specified buffer |

The following bits are defined in the MUON_BUF_STATUS register.

| Bit(s) | Bit Mask or Shift | Description |
|--------|-------------------------------|--|
| 1:0 | MUON_BUF_RNUM_MASK (_SHIFT) | Number of the muon buffer to be read |
| 3:2 | MUON_BUF_WNUM_MASK (_SHIFT) | Number of buffer currently being written |
| 6:3 | MUON_BUF_FULL_MASK (_SHIFT) | Bit map of full buffers |
| 7 | MUON_INTR_PEND_MASK (_SHIFT) | Interrupt pending if set |
| 10:8 | MUON_BUF_NFULL_MASK (_SHIFT) | Number of full buffers |

4.12 LED pulses

LED pulses may be generated under program control through the trigger module. (Ported original code developed by Roberto Assiro, Lecce.) Timing of the pulses is controlled by the trigger module. Amplitude of the pulses is controlled by the slow control micro-controller. There is one LED_CONTROL register at address LED_CONTROL_ADDR. The bit usage for this register is as follows:

| Bit(s) | Bit Mask or Shift | Description |
|--------|----------------------------|-----------------------------------|
| 0 | LED_NOW | Do LED pulse now |
| 1 | LED_ENAPPS | Enable LED pulse after PPS if set |
| 18:2 | LED_DELAY_MASK (_SHIFT) | # time bins delay after PPS |
| 29:19 | LED_PULSWID_MASK (_SHIFT) | Width of LED pulse in time bins |

Note that if LED_ENAPPS is set, that LED pulses will continue to be generated at the specified time after the PPS. This will continue until the LED_ENAPPS bit is cleared. If the timing of the LED pulse is not critical, LED_NOW can be used to generate a single pulse. LED_NOW must be cleared before another single pulse can be generated.

4.13 Scalers

There are 3 32-bit scaler instances. Each scaler instance accumulates counts of a single bin trigger instance. The count can be reset by writing (anything) to the scaler register. Unlike code versions prior to x010105y, these scalars are no longer tied to muon buffer intervals and they are not double buffered. Scaler incrementing is inhibited while scaler is being read. Each scaler block has the following format.

| Name | Address | R/W | Width | Description |
|---------------|---------------|-----|--------|---|
| Trigger Block | base+0:base+4 | R/W | Varies | Block defining dedicated trigger |
| SOURCE MASK | base+5 | R/W | 7 | Mask of sources for this scaler instance - no longer used |
| HOLDOFF | base+6 | R/W | 10 | Minimum number of bins between triggers - no longer used |
| SCALER | base+7 | R/W | 32 | Scaler value |

The trigger block has the same format as the single bin trigger block described above. The scalers count on the leading edge of a trigger satisfied condition. After counting, the scalers will not count again until after the input data has fallen below the trigger threshold.

4.14 AMIGA trigger

This trigger block produces the interface signals for the AMIGA trigger. Only one register is used.

| Name | Address | R/W | Width | Description |
|-----------------|---------|-----|-------|--------------------------|
| AMIGA GPS STAMP | 15 | W | 24 | GPS timestamp at trigger |

4.15 Other

The following registers don't fit into any of the groupings above.

| Address | R/W | Width | Description |
|---------------------|-----|-------|--------------------------------|
| ID_REG_ADDR | R | 32 | ID register |
| GLOBAL_CONTROL_ADDR | W | 1 | Some global control operations |

The ID registers contain the following bits.

| Bits | Description |
|------|--|
| 31:0 | 8 Hex digits: "xhddmmyy", where: "hddmmyy" represents the compile date (hour/day/month/year) of the code version release. |

The GLOBAL CONTROL register contains the following bits.

| Bit(s) | Description |
|--------|---------------------------------------|
| 0 | Generate a reset of the trigger logic |

4.16 Address Map

Both the address map and field definitions are defined in the file "sde_trigger_defs.h", the master copy of which is kept in the "sde_trigger" subdirectory of the "ip_repo" directory in the auger-prime-sde/uub-firmware git repository. A version corresponding to the integrated project snapshot is included in the wp5/sde_pl_hhddmmyy.tar file.

5 Shower Triggers & Memory

5.1 Register write order

To avoid spurious triggers, normally all registers should be loaded with their desired values before enabling any triggers in the SHWR_BUF_TRIG_MASK or MUON_BUF_TRIG_MASK registers.

5.2 Shower memory organization

After some consideration and testing, the organization of the ADC data in the shower memory buffers was chosen to simplify unpacking. Five memory blocks, containing 4 buffers each are used to store the traces. The format of each data word in TRIGGER_MEMORY_SHWR0 is shown below.

| Bits | Description |
|-------|-----------------------------------|
| 11:0 | WCD PMT0 low gain ADC |
| 15:12 | Low order 4 bits of filtered PMT0 |
| 27:16 | WCD PMT0 high gain ADC |
| 31:28 | Middle 4 bits of filtered PMT0 |

The format of each data word in TRIGGER_MEMORY_SHWR1 is shown below.

| Bits | Description |
|-------|------------------------------------|
| 11:0 | WCD PMT1 low gain ADC |
| 15:12 | High order 4 bits of filtered PMT0 |
| 27:16 | WCD PMT1 high gain ADC |
| 31:28 | Low order 4 bits of filtered PMT1 |

The format of each data word in TRIGGER_MEMORY_SHWR2 is shown below.

| Bits | Description |
|-------|------------------------------------|
| 11:0 | WCD PMT2 low gain ADC |
| 15:12 | Middle 4 bits of filtered PMT1 |
| 27:16 | WCD PMT2 high gain ADC |
| 31:28 | High order 4 bits of filtered PMT1 |

The format of each data word in TRIGGER_MEMORY_SHWR3 is shown below.

| Bits | Description |
|-------|-----------------------------------|
| 11:0 | Low gain PMT ADC |
| 15:12 | Low order 4 bits of filtered PMT2 |
| 27:16 | Spare ADC |
| 31:28 | Middle 4 bits of filtered PMT2 |

The format of each data word in TRIGGER_MEMORY_SHWR4 is shown below.

| Bits | Description |
|-------|------------------------------------|
| 11:0 | SSD low gain ADC |
| 15:12 | High order 4 bits of filtered PMT2 |
| 27:16 | SSD high gain ADC |
| 31:28 | Flags; sequence # for sanity check |

The flags currently just contain a sequence number running from 0 to 14 to verify integrity of the buffers.

The muon memories contain time stamped short blocks of data, intended mainly for single particle calibration data. The format of the first entry of TRIGGER_MEMORY_MUON0 is shown below.

| Bits | Description |
|------|----------------------------------|
| 30:0 | Time Tag for beginning of burst |
| 31 | 1, Indicating this is a time tag |

The format of the first entry of TRIGGER_MEMORY_MUON1 is shown below.

| Bits | Description |
|------|----------------------------------|
| 4:0 | Muon triggers for this burst |
| 31 | 1, Indicating this is a time tag |

The format of subsequent words in each block in TRIGGER_MEMORY_MUON0 is shown below.

| Bits | Description |
|-------|-----------------------------------|
| 11:0 | PMT0 high gain ADC |
| 15:12 | Flags; current used for testing |
| 27:16 | PMT1 high gain ADC |
| 30:28 | Flags; currently used for testing |
| 31 | 0, Indicating this is ADC data |

Similarly, the format of subsequent words in TRIGGER_MEMORY_MUON1 is shown below.

| Bits | Description |
|-------|------------------------------------|
| 11:0 | PMT2 high gain ADC |
| 15:12 | Low order 4 bits of burst counter |
| 27:16 | SSD high gain ADC |
| 30:28 | High order 3 bits of burst counter |
| 31 | 0, Indicating this is ADC data |

5.3 Reading Shower & Muon Memories

The shower and muon memories can be read via simple DMA, scatter-gather DMA, or via PDT.

Please see “trigger_test.c”, included in the sde_pld_hhddmmyy.tar file for examples of the readout sequence for the shower and muon memories.

6 Time Tagging Module

The file “Time_Tagging_Module_Specification_SDE_Upgrade_Version_3.pdf” is the primary documentation for the time tagging module. However, symbolic register addresses are also defined in the “sde_trigger_defs.h” header file for the convenience of writing code that references both the trigger module and the time tagging module. As for the trigger module registers, the symbolic names of the addresses all end in “_ADDR”. The following register names are defined:

| Register | Description |
|-----------------------|--|
| TTAG_SHWR_TICS | 120 Mhz counter at shower trigger |
| TTAG_SHWR_SECONDS | Seconds counter at shower trigger |
| TTAG_SHWR_PPS_TICS | 120 Mhz counter at last PPS before shower |
| TTAG_SHWR_PPS_SECONDS | Seconds counter at last PPS before shower |
| TTAG_MUON_TICS | 120 Mhz counter at muon buffer trigger |
| TTAG_MUON_SECONDS | Seconds counter at muon buffer trigger |
| TTAG_MUON_PPS_TICS | 120 Mhz counter at last PPS before muon buf. |
| TTAG_MUON_PPS_SECONDS | Seconds counter at last PPS before muon buf. |
| TTAG_PPS_SECONDS | Seconds counter at last PPS |
| TTAG_PPS_TICS | 120 Mhz counter at last PPS |
| TTAG_PPS_CAL | Calibration counter at last PPS |
| TTAG_PPS_DEAD_CTR | Dead time counter at last PPS |
| TTAG_STATUS | Status register |
| TTAG_CTRL | Control register |
| TTAG_ID | ID register, returns “ttag” |

The *TICS registers contain the 120 Mhz counter value in the low order 27 bits (TTAG_TICS_MASK). Bit 27 is always 0. In the TTAG_SHWR_TICS and TTAG_MUON_TICS, bits 31:28 contain the value of the event counter for the shower and muon buffer triggers respectively (TTAG_EVTCTR_SHIFT & TTAG_EVTCTR_MASK). The *SECONDS registers contain the seconds counter in the low order 28 bits (TTAG_SECONDS_MASK). The high order 4 bits are zero.

The TTAG_STATUS register contains bits useful for testing the time tagging module. Bits which get set in this register in response to stimuli can be reset via the TTAG_CONTROL register. The bit assignments in the TTAG_STATUS register are shown below.

| Bit | Bit | Description |
|-----|----------------|------------------------------|
| 0 | TTAG_MUON_TRIG | Muon buffer trigger occurred |
| 1 | TTAG_PPS | PPS occurred |
| 2 | TTAG_SHWR_TRIG | Shower trigger occurred |
| 3 | TTAG_DEAD_TIME | Dead time occurred |

The bit assignments in the TTAG_CONTROL register are shown below.

| Bit | Bit Mask | Description |
|-----|--------------------|---|
| 0 | TTAG_RESET | Reset the time tagging module when 1 |
| 1 | TTAG_CLR_PPS | Clear the PPS occurred flag |
| 2 | TTAG_CLR_SHWR_TRIG | Clear the shower trigger occurred flag |
| 3 | TTAG_CLR_MUON_TRIG | Clear the muon buffer trigger occurred flag |
| 4 | TTAG_CLR_DEAD_TIME | Clear the dead time occurred flag |

7 Digital Trigger

Left blank for now. Open for future expansion.